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Various Ambiguities in Generating and Reconstructing Laser Pulse Parameters

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1. Introduction

The pulse generation out of a laser cavity is a collaborative and evolving interaction process between EM fields (first spontaneous and then stimulated), and the intracavity device meant to introduce *mode locking* process. When we carry out the actual *mode lock* analysis, we do take into account of the interplay between all the temporal dynamics of the cavity gain medium, cavity round trip time and the evolution of the temporal behavior of the *mode locking* element (a saturable absorber or a Kerr cell). It is this mode locking element that facilitates the enforcement of *locking* the phases of the cavity spontaneous emissions towards in-phase stimulated emissions with its own temporal gating characteristics. On the observational level, this representation of the *mode locking* process has been serving us well (Milonni & Eberly, 2010; Krausz & Ivanov, 2009) and hence we have stopped questioning whether we have learned everything there are to learn about generating ultra short laser pulses (Roychoudhuri & Prasad, 2009; Roychoudhuri & Prasad, 2006; Roychoudhuri et al 2006). Consider the paradox discussed further in the next section. Homogeneously broadened gain media, like Ti-Sapphire laser, when succeed in generating *transform limited pulses*, mathematically it is equivalent to $a(t)\exp[i2\pi\nu_0t]$, an E-vector oscillating with a unique frequency ν_0 under the envelope function $a(t)$. A recent measurement does show such a unique E-vector undulation under a few fs pulse (see Fig.1b). What happened to all the longitudinal modes? Have they all interacted with each other and synthesized themselves into a single carrier frequency as is implied by the time-frequency Fourier theorem (TF-F)? Section-2 will show experimental results underscoring several *ambiguous* interpretations of measured data that we have been maintaining in the literature on mode lock physics. In Section-3 we will develop the methodology of thinking, *Interaction Process Mapping Epistemology* (IPM-E), which will help us discover the universal NIW-principle, Non-Interaction of Waves (Roychoudhuri, 2010), valid for all propagating waves within the linear regime. In Section-4 we will implement this IPM-E and the NIW-principle to show that all the case examples of ambiguities underscored in Section-2 can be resolved satisfactorily.

The purpose of this article is two-fold. The first purpose is to convince the readers that it is not the *phase locking* and *field-field interaction* between the *longitudinal modes* that re-groups the laser field energy into temporal pulses, rather it is the fast time-gating properties of the intra-cavity devices that are most important factors in advancing the field of ultra short pulse laser technologies. We believe that proper understanding of the deeper physical

processes behind light-matter interaction processes will clear out our minds from the clutter of ambiguities and then we can emulate nature's actual processes to advance the field at a rate faster than that has been taking place in the past. The second purpose is to draw attention to the need of articulating our methodology of thinking (epistemology) that goes behind gathering and organizing information related to a natural phenomenon, which then give rise to a working theory. Then the next generation of physicists, empowered by their newer and more precision measurement tools along with newer mathematical tools, can re-evaluate the foundational hypotheses behind the *working* theories for further advancement of physics. We have not yet reached the stage where we can safely assume that the basic edifice of physics has already been constructed; as if we just need to discover the pieces of stones of right shape and size to fit into the existing edifice.

2. Recognizing the fundamental ambiguities

All of our experimental data about any laser pulse parameter are gathered from quantitative measurements of some physical transformations experienced by some material medium, like a detector, after absorbing energy from one or multiple superposed light beams incident on them. Before we get into a better method of understanding of such processes, we need to establish that there does exist ambiguities behind the very concept of *mode lock* theory.

2.1 Can superposed modes create a new mean frequency?

Current literature (Milonni & Eberly, 2010; Krausz & Ivanov, 2009; Siegman, 1986) has accepted that *mode locked* laser pulses are generated by the summation process that take place between the monochromatic beams of electromagnetic waves with carrier frequencies having a periodic separation of $\delta\nu = c / 2L$. Eq.1 is set up for N longitudinal modes, all in phase with equal unit amplitude having a cavity round trip time as the inverse of mode spacing, $\tau = 1 / \delta\nu$:

$$E_{sum}(\nu_0, t) = \sum_{n=0}^{N-1} e^{i2\pi(\nu_0 + n\delta\nu)t} \approx \frac{\sin N\pi\delta\nu t}{\sin \pi\delta\nu} e^{i2\pi\nu_0 t} \equiv a(t / \tau) e^{i2\pi\nu_0 t} \quad (1)$$

The normalized intensity envelope for the pulse train, in two different mathematical forms, is given by:

$$I(t) = (1 / N^2) |E_{sum}(\nu_0, t)|^2 = \frac{1}{N^2} \frac{\sin^2 N\pi\delta\nu t}{\sin^2 \pi\delta\nu t} \equiv \frac{1}{N} + \frac{2}{N^2} \sum_{p=1}^{N-1} (N-p) \cos[2\pi p\delta\nu t] \quad (2)$$

The operational implications of Eq.1 and 2 are that the superposed continuous longitudinal cavity modes interact with each other by themselves and re-arrange their temporal energies into a new train of *mode locked* pulses and convert the periodic mode frequencies into a new single mean frequency ν_0 (see Fig.1a). Surprisingly, a novel measurement process does reveal that the electric vector oscillate in a single carrier frequency (see Fig.1b) if the laser is stabilized with great care. This clipped out 4.5 fs pulse was generated by a *mode locked* Ti-Sapphire laser, a *homogeneously broadened* gain medium (Krausz & Ivanov, 2009).

Now, a question to the reader. Can collinearly superposed propagating EM waves in the linear domain generate a new E-vector frequency without the aid of any interaction with some material medium? Can the laser gain medium itself carry out this summation? But

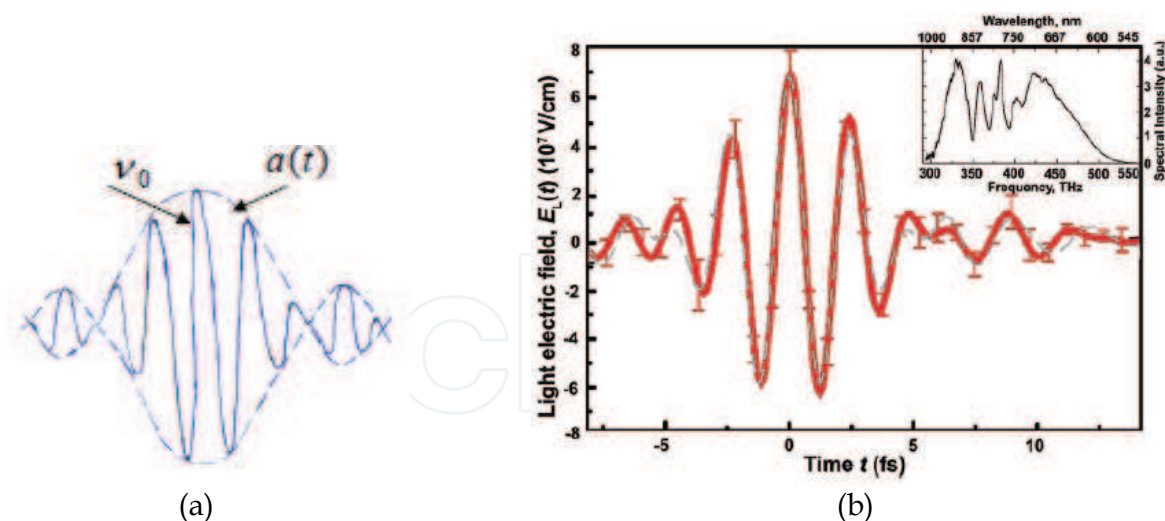


Fig. 1. (a): A mathematical envelope function (dashed curve) implied by Eq.1 is sketched that defines the time varying amplitude for a single E-vector oscillating at a unique frequency ν_0 . Only a single major pulse out of an infinite train has been shown. (b): Demonstration of the existence of a single carrier frequency in a 4.5fs pulse by directly measuring the harmonically undulating E-vector strength (taken from Fig.12 in Krausz & Ivanov, 2009).

then, why do we need high intensity laser beams propagating through some special *nonlinear material medium* with preferred orientation to generate sum or difference frequencies?

Contradictions and paradoxes abound in this field. A He-Ne laser with *inhomogeneously broadened gain medium*, when *mode locked*, its longitudinal modes do not get converted into a single central carrier frequency (see Fig.2b), even though the pulse width (Fig.2a) and the intrinsic line width of the individual longitudinal modes (Fig.2c) corroborate extreme phase stability between the modes needed for the required *mode locking* condition (Allen et al, 1969). If Eq.1 does represent the real physical process behind *mode locking*, and if that is corroborated by the result of Fig.1a and c, then we should conclude that Allen et al did not really achieve *mode locking* in spite of *locked* phases between the modes!

2.2 Can a homogeneously broadened gain medium oscillate in all the allowed cavity modes?

Now, another question for the reader. An excellent Ti-Sapphire crystal, in a CW laser cavity, runs normally at a single longitudinal mode determined by the gain-line center where the gain is highest because the Ti-atoms are embedded in a homogeneously broadened gain medium. Can the spectral behavior of Ti-atoms become inhomogeneously broadened under mode locked conditions, allowing all the potential cavity modes to oscillate, as allowed by *inhomogeneous* Ne-atoms in a He-Ne gas laser? If *mode locking* field-field interaction is the cause behind obtaining ultra short pulses from a Ti-Sapphire laser, then the gain medium needs to become functionally inhomogeneously broadened! The alternate explanation is that it is the periodic Fourier side band frequencies, matched with the cavity modes, which provide seeds for multi frequency oscillation (Milonni & Eberly, 2010) even though the gain medium always remains homogeneously broadened. Then the question arises as to which physical process carries out the Fourier decomposition of a pulse envelope to generate the

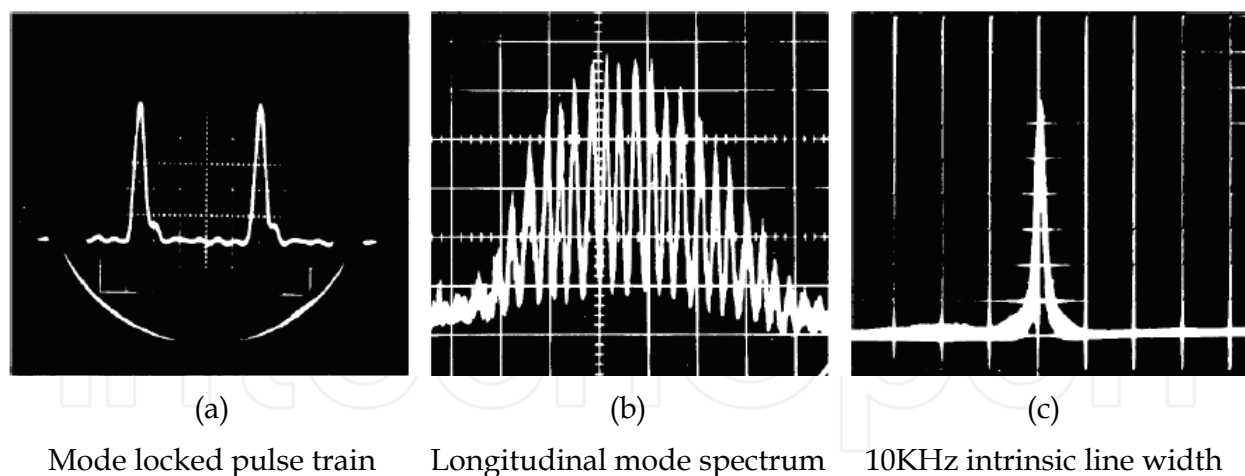


Fig. 2. Experimental data from a mode-locked He-Ne laser showing intensity vs. time for a mode-locked pulse train in (a), longitudinal mode spectrum in (b), and the heterodyne high resolution line width, 10KHz, of one individual laser mode in (c) (from Allen et al, 1969).

longitudinal mode seeds? Note that any device that can carry out the Fourier transformation process, must possess some memory to be able to first *read* the shape of the *entire amplitude envelope* of the pulse and then *carry out* the mathematical *Fourier decomposition process* to generate *real physical Fourier frequencies* to promote stimulated emissions at these *side band frequencies*! However, we know that the response time of excited atoms to stimulating radiations are well below pico seconds, if not femto seconds, or even less.

2.3 Can the time-frequency Fourier theorem (TF-FT) be a principle of nature?

For the Fourier side bands to exactly match the cavity allowed mode frequencies, the oscillating amplitude envelope and its periodicity must already correspond to the final *mode locked* envelope and the pulse train. The possibility exists that the spontaneous emissions accidentally gets in phase and opens up the stuarable absorber gate and a pulse starts to reverberate through the cavity while iteratively perfecting itself towards the ideal mode locked envelope, and at the same time, the Fourier decomposition process of the amplitude envelope (generation of the side band frequencies) also continues to evolve into a perfectly matching frequency set with the cavity modes. For this temporal evolution to work in favor of our current hypothesis, the time frequency Fourier theorem (TF-FT) must be a physical principle of nature. In other words, the pulsed light amplitude, even when the carrier E-vector is oscillating in a unique single frequency, must have inherent affinity to re-represent themselves as the summation of periodic *Fourier frequencies* as is demanded by the TF-FT. Then it is possible that the Ti-atoms will be literally stimulated by all the allowed cavity mode frequencies, as per TF-FT. Mathematical logic wise it is plausible. Can this be the physical reality? Then the evolving weaker Fourier side band frequencies must be able to compete with the stronger gain line center. Further, if the TF-FT is a physical principle of nature, then superposed coherent light beams must be able to interact with each other and re-distribute their energy in time and space to create energy pulses without the need of mediation of any material medium. In other words, inhomogeneously broadend lasers, like He-Ne, with very high-Q cavity (narrow mode width and high coherence time), should show spontaneous break up into random pulsations, which is not observed in reality.

2.4 Why regular CW He-Ne lasers show mode-lock-like pulsations?

However, a fast detector stimulated by a regular CW He-Ne laser does show oscillatory current exactly mimicking *mode locking* behavior! Consider the measurements carried out in our lab using an ordinary commercial CW He-Ne laser as shown in Fig.3 (Lee, 2004; Roychoudhuri et al, 2006). Fig.3a shows the spectrally resolved longitudinal modes of the laser as displayed by an optical spectrum analyzer (OSA). This OSA was a very slowly scanning Fabry-Perot spectrometer and the output spectral lines never showed any pulsations. The result implies that the laser is running CW with three dominant modes and two weak modes under the usual 1.5 GHz Ne-gain envelope. However, Fig.3b shows the intensity envelope that implies the laser is *mode locked*, even though it is not. The data was recorded through a combination of a high speed detector and a high speed sampling scope. Fig.3c is a computer simulation of the resultant amplitude, which is the sum of the five modes shown in Fig.3a. When the output of the high speed detector was analyzed by an electronic spectrum analyzer (ESA), one can identify the self-heterodyne signals (beat between all the individual modes), as shown in Fig.3d. This clearly corroborates the result of Fig.3a that the optical frequencies (modes) are oscillating independent of each other and have not merged into a mean frequency as predicted by Eq.1, or the intensity trace of Fig.2b may imply.

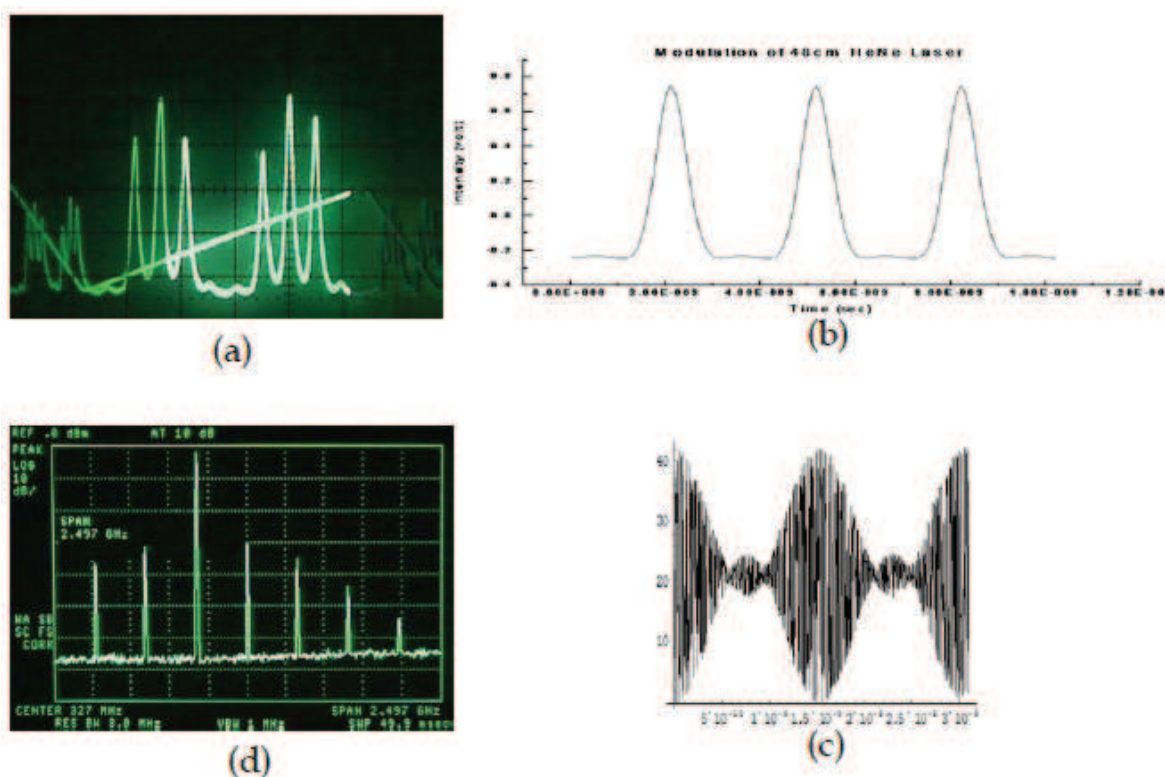


Fig. 3. Is this He-Ne laser mode locked? Data gathered from an ordinary He-Ne laser. (a) Longitudinal modes resolved and displayed through a very slow scanning Fabry-Perot spectrometer. (b) Laser intensity trace recorded by a 40 GHz sampling oscilloscope as detected by a 25 GHz detector. (c) Computer model of the amplitude envelope for the sum of all the modes displayed in (a) as if they are in same phase (mode locked), which corroborates the measured intensity envelope in (b). (d) Display of the 25 GHz detector output as analyzed by an electronic spectrum analyzer. [from Roychoudhuri et al, 2006].

2.5 Is synthetic mode locking possible?

Next we present another experiment to test whether simple superposition of a set of periodically spaced frequencies with steady mutual phase coherence, can automatically generate *mode lock* pulses. Fig.4a shows the schematic diagram of the experimental set up. With the help of an acoustooptic modulator, a single frequency (ν_0) beam from an external cavity stabilized diode laser is converted into three coherent beams of three periodic frequencies (ν_0 & $\nu_0 \pm \delta\nu$) and then superposed into a single collinear beam. The beam was then analyzed to check whether it became *mode locked* and pulsing with a single carrier frequency. The intensity envelope as registered by a 25GHz detector and then displayed by a 40GHz high speed sampling scope is shown in Fig.4c; the trace does correspond to a pulse train that would be generated by a *three-mode-locked* laser. However, a simultaneous spectral analysis of a sample of the same beam through a slowly scanning Fabry-Perot spectrometer displayed the presence of the original three frequencies (ν_0 & $\nu_0 \pm \delta\nu$). If they were *mode locked* then, as per TF-FT, we should have registered only the mean (central) frequency ν_0 . Analysis of the current from the high speed detector by an electronic spectrum analyzer (as in Fig.3d, but not shown here), had displayed two mode-beating lines at $\delta\nu$ and $2\delta\nu$, corroborating that Fourier synthesis did not take place even though the high speed detector current implies *mode locking*! Clearly some apparently successful mathematical modeling of data can mislead us to wrong conclusions. Light-matter interaction processes behind all measurements must be investigated thoroughly before convincing ourselves about any specific properties of light.

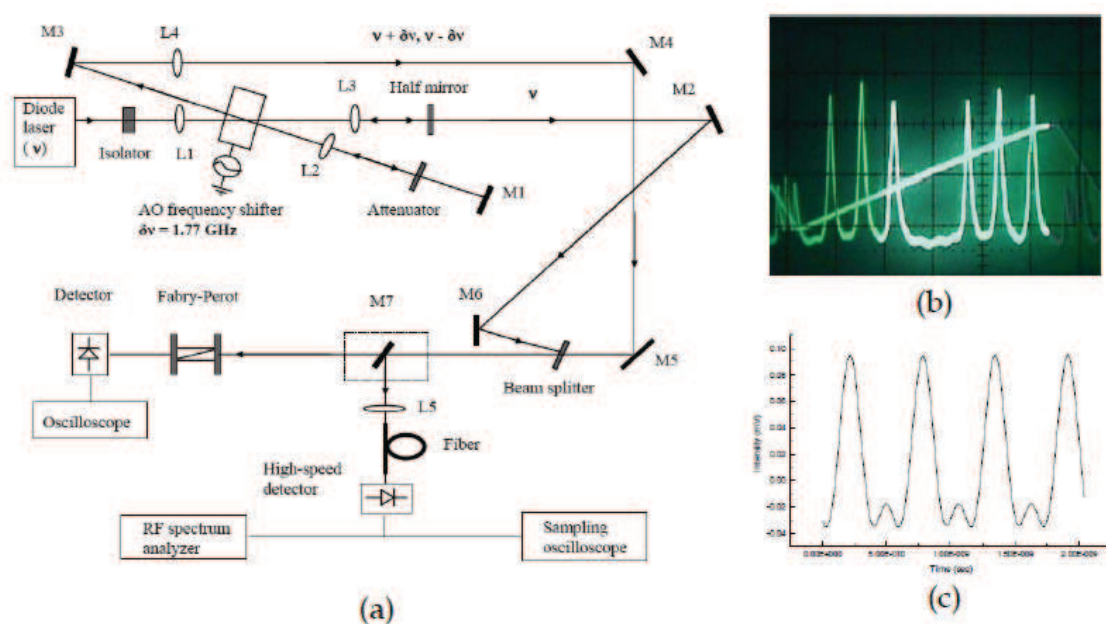


Fig. 4. (a) shows experimental arrangement to generate three periodically spaced coherent frequencies (modes) from an external-cavity-stabilized single frequency diode laser using an acoustooptic modulator. The beams are then collinearly superposed and analyzed for possible mode-lock behavior. (b) shows the spectral display of the three independently oscillating frequencies through a slowly scanning high resolution Fabry-Perot spectrometer. (c) displays the photo-electric current on a high speed sampling scope generated by a high speed photo-detector. (from Lee, 2004; Roychoudhuri et al 2006).

2.6 Can autocorrelation data unambiguously determine the existence of ultrashort pulses?

Next we present experimental results to demonstrate that a measured train of autocorrelation spikes, which may imply the existence of a train of ultra short pulses in a laser beam, may not necessarily represent the actual physical reality! The data shown in Fig.5 were generated using a Q-switched diode laser with a saturable absorber facet (Roychoudhuri et al, 2006), which was generating a steady train of 12ps pulses at about one millisecond interval. Fig.5a shows the time averaged spectrum generated by a high resolution grating spectrometer. There are some 32 modes present and the spacing is about 0.4839nm or $\delta\nu \approx 200$ GHz (199.74 GHz) at $\lambda = 852.5$ nm. The experimental resolving power from the graph is clearly narrower than 100GHz. This is also supported by computation using the TF-FT corollary, $\delta\nu\delta t \approx 1$. The pulse width of $\delta t = 12$ ps, derived by Lorentzian fitting from the autocorrelation trace of Fig.5b, implies that the individual spectral fringe width should be about $\delta\nu = 83.3$ GHz, which is clearly smaller than 100GHz, as observed above. The cavity round trip time is 5ps (1/200GHz), which is less than half the Q-switched pulse width. So, the Q-switch pulse width had time to carry out a couple of reverberations and establish cavity longitudinal modes through stimulated emissions.

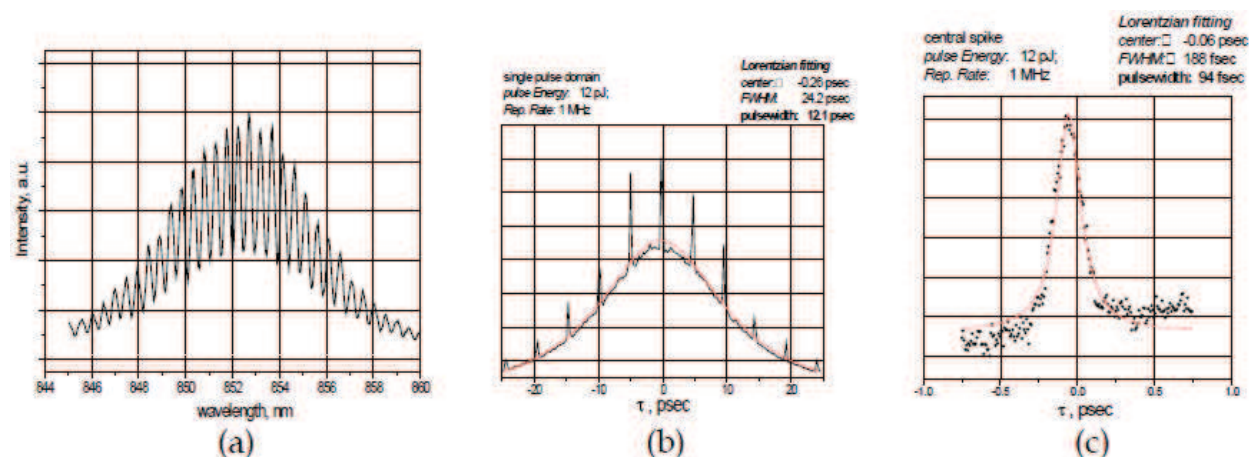


Fig. 5. Has this Q-switched 12ps diode laser (with saturable absorber facet) produced 94 fs mode locked pulse train? (a) Time averaged multi mode optical spectrum. (b) Non-colinear 2nd harmonic autocorrelation trace with an apparent train of 94 fs pulses within the 12 ps Q-switched pulse. (c) Repeated measurements of the central fs autocorrelation trace [from Roychoudhuri et al, 2006].

Let us now draw our attention to the 94fs spikes riding on the autocorrelation trace of Fig.5b at exactly the interval of the cavity round trip delay. Do we really have fs mode locked pulses within each 12ps Q-switched pulses? As per $\delta\nu\delta t \approx 1$, the spectral line width corresponding to 94fs pulses should be more than 10,000GHz. But the half width of the spectrum is less than 3000GHz. Of course, one may argue that the pedestal (lower envelope of the spectrum) of Fig.5a shows the spectral broadening due to the fs spikes and it is not the spontaneous emission background. It is a difficult proposition because in a 5ps cavity a 12ps pulse does not have enough time to over-ride the dominance of spontaneous emissions when the diode is pumped by current pulses of nano second duration and kilo amperes peak value repeated at KHz.

3. Discovering the principle that resolves the ambiguities

Why do we need to discuss the methodology of thinking (epistemology) in a hard-core scientific paper? Since this is not the normal custom, some readers should feel free to skip this section and jump to Section-4 and find the resolutions of the ambiguities raised in the last section. Then they can come back to read and appreciate the utility of this section on epistemology. Here we develop an epistemology, we call the Interaction Process Mapping Epistemology (IPM-E) whose objective is to visualize the invisible interaction processes that give rise to the measurable data. Current physics stops once we have successfully modeled the measured data, which we call Measurable Data Modeling Epistemology (MDM-E). When IPM-E is applied systematically to light-matter interaction processes behind registration of optical superposition effects, one can discover that, in reality, superposed light beams do not interact (interfere) by themselves. We call this NIW-principle since Non-Interaction of Waves (NIW) is a general principle of nature in the linear regime, which has remained unrecognized due to our consistent epistemology of ignoring what is not directly measurable or observable.

3.1 Introducing the Interaction Process Mapping Epistemology (IPM-E)

A careful analysis of the methodology of our thinking behind the development of theories (information gathering and organizing) is a vitally important task because it will allow us to critically and objectively evaluate the various steps that went behind existing working theories and then modify/correct them as our technologies for all measurements keep on dramatically improving. We know that all human constructed theories are necessarily incomplete as they have been organized based on insufficient information about the universe; and everything in the universe is interconnected, sometimes overtly and other times subtly. We still do not know what an electron is. And yet, our current knowledge of the universe has exploded during the last few hundred years through several punctuated *revolutions* as claimed by Kuhn [Kuhn, 1996] in modeling observable information. Over the centuries, we have clearly experienced that all of our theories have been iteratively corrected, improved and/or replaced as our sensor (measurement) technologies have been enhancing with time. But this dynamism in physics has steadily *slowed down* over the last several decades as we have remained focused on maximizing the *utilities* of current *working* theories, instead of iteratively improving upon their foundational hypotheses. This *slow down* can be appreciated from the list of recently published books by many authors, some of whom are very well known (Silverman, 2010; Woit, 2007; Laughlin, 2006; Smolin, 2006; Penrose, 2005). In contrast to complex epistemologies by these authors, we define a very simple and pragmatic epistemology that, beside solving the ambiguities encountered in the field of pulsed lasers, also solves many other paradoxes encountered in both classical and quantum optics presented elsewhere (Roychoudhuri, 2010; 2009a; 2009b; 2009c; 2008; 2007a). As mentioned earlier, this is because the core epistemology of physics has remained basically same for several centuries: *MDM-E*. While measurable data had been, are, and will remain as the key validation approach for all of our theories, we need to graduate to the next deeper level of epistemology so we can understand and visualize the invisible interaction processes that give rise to the measurable data. We have named this epistemology: *IPM-E*. In reality, inventors of new technologies have always tended to use IPM-E without articulating as such. They have always appreciated nature as a creative system engineer. They think like *reverse engineers* and visualize the invisible interaction processes in nature using their imaginative faculty and then emulate different natural processes to invent

and innovate useful new technologies. This has been the most vitally important practical step behind our successful evolution. It has been the unusually rapid rate of technology inventions that has helped humans to become the most dominant species of the biosphere. We have gone so far ahead of other species using our technologies that we have started to ignore that we are just another species and we cannot and must not try to defy the laws behind the biospheric and the cosmopheric evolutions.

Our MDM-E guided mathematical models seem to be working as the measured data are modeled reasonably well and can predict new measurements quite accurately. And yet, we have all these confusing ambiguities, paradoxes and contradictions, identified in the last section. Clearly MDM-E is somehow falling short of helping us visualize the interaction processes behind laser *mode locking*! We must be missing something fundamental behind our assumption of summing the various light beams (mode locking). We do not accept a generic curve fitting polynomial as a proper theory for a phenomenon under consideration because it contains too many free parameters. However, when it is a compact and elegant mathematical relation like that of Planck's Blackbody Radiation, we are elated because it also leads to further prediction of new phenomena that we have never measured before. However, Planck's relation still does not help us visualize the physical processes behind radiation absorption and emission. Otherwise quantum mechanics would have been invented by early 1900. Planck proposed that only the energy exchange process is quantized as $\Delta E_{mn} = h\nu_{mn}$, but once the released quantum of energy ΔE_{mn} evolves into an EM wave packet, it propagates diffractively as a classical wave. But, within five years of Planck's discovery, in 1905 Einstein discovered some *quantumness* in the photoelectric data and assigned this *quantumness* to the wave packets of light (spontaneous emissions), rather than to the binding energies of the electrons, and declared light to be *indivisible quanta* and missed the opportunity to discover quantum mechanics himself. It was Bohr who formally proposed that the electron binding energy was quantized in atoms in 1913, which was evident from Ritz-Rydberg formula for atomic spectral lines. But the formulation of formal quantum mechanics (QM) had to wait until 1925. The dominant interpretation of this QM categorically instructs us not to waste time in trying to visualize the details of interaction processes between electrons, protons and neutrons that have build the entire observable material universe! One should also note that this QM *does not have a rigid hypothesis that only quantum entities can exchange energy with each other*. Otherwise, a classically accelerated electron in a He-Ne discharge tube could not have shared a fraction of its *kinetic energy* in raising the quantized Ne-atoms from their ground to an upper excited level! And before the end of the decade of *quantum revolution*, Dirac assigned *self-interference* property to these *indivisible quanta*, we now call photons (Dirac, 1974). And, now, over the last couple of decades, we have been claiming to successfully carry out quantum communication, computation and encryption exploiting this unique *self-interference* property of single *indivisible* but *nonlocal* photons.

Remarkably, even though our instruments, interferometers and detectors, are very well *localized* (physically finite) in space, *single photons* are unlocalized in a coherent CW beam as if it is like a Fourier monochromatic mode. We assume that they are equally well *unlocalized* within a 0.3 micron long (1fs) pulse since the pulse is apparently built out of many infinitely extended Fourier monochromatic modes (Fourier transform of the pulse envelope). The point is MDM-E guided successful theories are not guiding us to discover unambiguous *pictures* as to how nature really carries out its interaction processes. We need something better! So, the

author has initiated publications and an international conference series to promote deeper investigation on the nature of light (OSA 2003; SPIE 2005, 07, 09). Readers are very welcomed to join us to accelerate the growth of optical science and engineering with a deeper foundation; the 4th biannual conference is set for August 2011 during the SPIE Annual Conference.

The seed for seeking a better epistemology is already built into MDM-E. We want to understand all the cosmic logics (laws) behind all the interaction processes that are behind the dynamically evolving cosmic system. But we do not have any direct access to these logics. However, our successful theories organized as mathematical equations represent strict relationships between cause and effect and match data to model potential cosmic laws. And the long list of staggering successes of our endeavor clearly imply that the laws of nature must be very logical, causal and hence *invariant*. Otherwise we could not have achieved so much successes in understanding the processes behind the evolution of the cosmic system. It is then safe to conclude that the interaction processes guided by these cosmic laws must also be *invariant*, albeit invisible. If we want to extract reality out of nature, we must anchor our epistemology with something in nature which is accessible to us through our measurement and theorizing processes and yet invariantly connected to the cosmic logics more deeply than the measurable data alone. It is then logically safe for us to shift our epistemology one-step deeper to construct and refine theories based upon our attempts to visualize the interaction processes, rather than carrying out only *curve fitting* of measured data. Curve-fitting MDM-E provides neither the guidance, nor the incentives, and nor the challenges necessary to try to *iteratively enhance* our already *working* theories, but IPM-E does. The interaction processes, being invisible and elusive, pose constant mental challenges to us. And yet they represent nature's invariant referent source for gathering feedback information and keep on refining them iteratively for as long as it takes! All knowledge must be advanced and refined through iterative feedback loop. Successes with MDM-E brings complacency, while construction of process map achieved with IPM-E keeps on bringing perpetual challenges. A map never becomes the actual terrain! Our sustained and successful evolution will be assured by such an epistemology. However, IPM-E does not replace MDM-E. IPM-E coopts MDM-E as its foundational tool but empowers it with the iterative debating tool to challenge all *working theories* and force them to evolve or make room for new theories.

Since invention of new technologies fundamentally rely upon our capability of emulating various interaction processes in nature and the concomitant cosmic logics (laws), it will be more productive for us to think like reverse engineers, as far as nature is concerned. We must stay focused on becoming discoverers of the laws of nature rather than trying to invent them and then tell her how she should function! All human scientific logics (epistemology) must keep on evolving to refine our grasp of unknown cosmic logics that enforce continuous cosmic evolution including our minds.

To further appreciate the utility of IPM-E, we need to dissect the epistemological steps behind creating theories. The two key steps are (i) information gathering/generating challenge (IGC) and (ii) information organizing challenge (IOC). The first step is also known as the *Measurement Problem* in quantum philosophy and the second step may be identified as the eternal *Theorizing Problem*! This is because an analysis of the first problem makes us aware that we are forever challenged by nature in gathering complete information about even the simplest entity in nature we try to study. We may call it the Incomplete Information Challenge (IIC)! For example, the electron was discovered in 1897 by J. J.

Thompson and is being analyzed by tools of quantum mechanics since 1925. It is being utilized in engineering machines like free-electron lasers and electron microscopes for many decades. Yet, even today, we still do not really know its real structure and from where the electron gets its charge and mass. Accepting wave-particle duality as the final answer that physics can provide is akin to accepting a moving bulge under a carpet as the final limit of our knowledge for fear of lifting the proper carpet corner and discovering a running mouse! We must not *suppress* or *moth-ball* deeper questions related to *interaction processes* by imposing further layers of sophisticated mathematical models. We cannot solve the *Measurement Problem* and the IIC driven *Theorizing Problems* by inventing more and more mathematical constructs alone. Mathematical tools are our key guide to help us extract many new information, but tools cannot be used as substitutes for the information we seek.

3.1.1 Information generating and gathering challenge (Measurement Problem).

The founders of Quantum Mechanics correctly recognized that there is a “Measurement Problem” in QM. However, the author believes that the problem is more generic than has been assumed. The problem pervades all scientific endeavors as we try to generate and gather information about anything we try to study in nature. This information challenge or measurement problem cannot be overcome by any clever mathematical theorem! It will be obvious once we delineate the simple steps behind any experiment or information generating/gathering process.

1. **Measurable Transformation:** We can measure only some physical transformations in our sensors triggered by physical transformations experienced by the interactants under study. [No need to invoke God or human consciousness!]
2. **Energy Exchange:** All physical transformations require some energy exchange between the interactants under study and the sensor used to register the transformation.
3. **Force of Interaction:** Energy exchange, and consequent transformations, must be guided by an allowed force, or forces, of interaction(s) between the interactants and our sensors. “Classical” interactions allow continuously variable energy exchange dictated by the experimental context. QM interactions in the linear domain (transition between pre-existing QM levels) allow only discrete amount of “resonant” energy exchange.
4. **Physical Superposition (Sphere of Influence) or “Locality” of All Interactions:** Interactants must be within each other’s sphere of influence to be able to interact under the guidance of an allowed force to transfer energy and then undergo transformations. Thus “locality” can be of galactic distance for galaxies under gravitational force, or it can be 10^{-15} meter for strong nuclear force between nucleons.

Corollary 1: Impossibility of Interaction-free Transformation (IIT): It is self evident from the items described in 1 to 4 to above.

Corollary 2: Incomplete Information Challenge (IIC): We can never gather all the information about anything through any experiment since the details of none of the interaction processes and those of the interactants are completely known to us. Further, almost all measuring instruments require amplification of the original information created by original transformation through new interaction step(s) in the detecting system. And we know that we can rarely transmit (or, transfer for recoding as data) the original but unknown information with perfect fidelity through complex systems that have their own unknowns. We are after Cosmic-Logics (rules of interactions)! They are not directly accessible through Data-Math model alone.

3.1.2 Information organizing challenge (theorizing problem)

Purpose of physics is to discover the unknown *cosmic logics* (laws) and the underlying invisible *interaction processes* that we can emulate to create technologies to assure our *sustainable evolution*. We are challenged for ever! Through millennia of observations, we found that nature behaves in logical patterns. So, we have refined the faculty of *human logics* to *frame logical questions* that help us discover *conceptual continuity* between diverse observations. Then we bring some *cause-effect logical congruence* between them by inventing well-articulated *hypotheses* to compensate for the missing information. For a quantitative best fit (curve fitting), we have then invented a new language of more refined logics, we call mathematics or *mathematical logics*. In other words, *human logics* frame questions and hypotheses about *cosmic logics* to match the organized observations and then create a quantitative fit to the data using *mathematical logics*. The use of a generic n -th degree polynomial could have been the simplest choice. However, we have found that simpler and more elegant a mathematical expression (theory) is, more success it shows towards predicting newer phenomena, leading us to believe that we are getting closer to the actual cosmic logics (laws). Continuous endeavor to iteratively refine the map of invisible interaction processes will take us closer and closer to the real cosmic logics. However, we know that the construction of a very realistic map can never be the substitute for traveling in the real terrain!

3.1.3 Importance of identifying and articulating the epistemology

In the last section on information gathering, we have identified the perpetual IIC imposed on us by nature. It is the IIC that forces us to hypothesize, or invent (dream up) information that was not directly available through measured data. This is where the genius minds of Galileo, Newton, Faraday, Maxwell, Einstein, etc., appear to us so impressive and worthy of reverence. Importance of the epistemology now becomes apparent. *Framing the question determines the answer one can extract out of nature's interaction processes*. And framing the question is dictated by the personal epistemology, or the mode of thinking, which is a complex product of individual genome and how that genome absorbs, nurtures and cultivates the individual mind towards his/her personal epistemology. A small subset of a very complex but organized system can be modeled by many different sets of rules, none of which may exactly coincide with the original set of rules that has organized the whole system (Johnson, 2009). A simple illustration could be obtained by giving a very intelligent child to solve the puzzle of the world map, but with all the pieces inverted and randomized. The child most likely will quickly succeed in assembling Australia, Madagascar, England, Italy and some other parts of the world having unique boundaries. Inverting the partially *solved* puzzle will demonstrate that there are many wrong pieces perfectly fitting inside some of the *solved* countries! This is because the puzzle pieces are built out of only a few set patterns (except the boundaries). Based on our current state of knowledge, the cosmic evolution is being guided by only a few cosmic logics (laws), perhaps constituting only four forces as theorized now. So, as our scientific epistemology evolves further, we should not be surprised to discover that some of our mathematical logics (theories) that have fitted the data very well, are *happy coincidences*, like segments of the solved world map-puzzle. We should remain humble enough to hold our judgments from declaring that we have already found the *God's Equation* (Aczel, 1999).

Our attempts to iteratively try to refine our imagined map, personally or collectively, to depict a particular interaction process will be greatly benefited if we explicitly lay out our personal epistemologies as to how we have framed our questions, what hypotheses we have

constructed to fill up the missing information (IIC), etc. In this context, it is rather surprising to recognize the 2500 year old advice by Gautam Budhha of India: To visualize the invisible cosmic elephant, it is better to learn to think the way the blind people do and then collaborate to draw a preliminary sketch (map) of the perceived elephant and then keep on improving upon it iteratively through perpetual debates. That our personal perceptions are dictated by our survival needs, and hence far from our capability of objective analysis of actual reality, was brought to our understanding by Buddha by *framing a brilliantly simple question*: How can blind people *observe* and *model* an elephant? Objectively speaking, we are blind! Our neural network literally *imagines* images, smells, tastes, pains and pleasures out of the various sensorial inputs (registered *transformations* in our bodily measuring instruments!) for the key purpose of survival and successful evolution. We must now learn to use our free brain to go beyond survival and start consciously constructing road-maps for our purposeful evolution.

3.2 Applying IPM-E to discover the NIW-principle (Non-Interaction of Waves)

Detection of the presence of electromagnetic waves (energy) is always carried out by some material based detector that has the intrinsic capability to respond to the incident oscillatory electric field and then absorb some energy from the field and consequently undergo some measurable transformation. We never *see* any electromagnetic waves, *visible or invisible*. We can only indirectly interpret the presence of some EM wave(s) from the various transformations (*meter readings*) presented to us by our measuring instruments based on initial transformations experienced by the key sensors (detectors). In fact, EM waves do not possess any real physical attribute that we can call color. Frequency is the real physical parameter. Three types of retinal molecules in our eyes, sensitive to *red*, *green* and *blue* frequencies, communicate with our visual cortex to generate the interpretation of colors, which have evolved for the necessity of our successful evolution. Successful evolution-congruent neural networks, which are at the root of our personal epistemologies, are not the most reliable thinking machines to discover cosmic logics in a straight forward manner. Their job is to successfully adapt for survival to the changing environment generated through the interplay of cosmic logics within the evolving cosmic system. Development of scientific epistemology, to see the world as is, not as required for survival, requires extra awareness to systematically cultivate objective thinking. We need to learn to *observe* what are happening *inside-the-boxes*, first inside our own active brains, then within the biosphere and finally in the cosmo-sphere, while *standing outside-the-box* using our evolved imaginative *free-brain*. This is where IPM-E can play the role of an important thinking tool for consciously constructing our *purposeful* evolution. Darwin's *Natural Selection* have been helping us to evolve as a species. But the evolution of our free-brain is being both accelerated and strongly guided by our *Cultural Selection* (Roychoudhuri, 2010a). Our conscious awareness of this *Cultural Selection*, e.g. IPM-E in preference to MDM-E, and eventually, something superior, is needed to assure the successful evolution of human scientific minds. We can then take the responsible ownership of the biosphere and then eventually graduate to become *cosmo-zens* (cosmic citizens)!

Let us come back to the application of IPM-E to understand the interaction processes behind *interference of light*. What we call *interference of light* is, in reality, a resultant transformation experienced by some detector in response to simultaneous stimulations induced by multiple superposed beams due to their simultaneous presence on the detecting molecule. If its intrinsic properties do not allow it to experience simultaneous stimulations, it can not report any superposition effects; and there is no interference! Responses (or measured

transformations) of all light detectors are further complicated by the follow-on steps through which we amplify and register the final transformations as recorded data. In every step, we may lose some information about the original transformation we intend to measure due to further interaction steps during these amplification stages (recall IIC).

The reader may now raise the *interaction process* based question as to whether (i) the superposed EM waves first create a new resultant EM wave and then impose the effective stimulation on the detector, or (ii) the detecting molecule separately but simultaneously responds to all the oscillating E-fields. The mathematical model and experimental data are in favor of the latter proposition. The resolution was carried out by using a two-beam interferometer with variable polarizers in its two arms (Roychoudhuri & Barootkoob, 2008). Coherent or not, EM waves cross through each other, or propagate collinearly, without creating any transformations in their individual physical parameters. This property of Non-Interaction of Waves (NIW) is a generic principle of nature. No propagating waves interact with each other in the linear domain. They pass through each other unperturbed without any permanent re-arrangement in their phase or energy distribution, either in the space or in the time domain. This is the universal NIW-principle (Roychoudhuri, 2010b). Otherwise the fidelity of our daily vision (due to light waves) and hearing (due to sound waves), critical to our successful evolution, would not have worked! If the light beams interacted with each other to create new energy distributions, our Radios would not have been able to extract clear music out of multiple carrier frequencies and our internet signal, utilizing WDM (Wavelength Domain Multiplexing) technologies, would have created undecipherable heterodyne noise instead of clear data for each channel.

In reality, Hyathem around 1080, clearly noted in his book that light beams belonging to different sources do not interact with each other (Ronchi, 1970). He simply observed the images of a set of candles formed through the pinhole of a *Camera Obscura*, which remained unaltered even when he lit or unlit different candles. This observation should not be explained away assuming *incoherence* of light (Roychoudhuri, 2006b). Surprisingly, Dirac during late 1920's, while quantizing the electromagnetic field, and based on already developed Bose-Einstein statistics, clearly recognized that photons are non-interacting Bosons. And yet, to accommodate the apparently successful classical model of *interference of light*, declared, "...each photon then interferes only with itself" (Dirac, 1974) as if self-interference (appearance and disappearance) of a stable elementary particle is logically self-consistent with our mathematical logics and *cause-effect* driven cosmic logics! In fact, computation of direct photon-photon interaction, or scattering cross section in the *material-free vacuum*, has been found to be unmeasurably small (Tomasini et al, 2008).

We conclude this section on epistemology by raising the following questions to the readers. Could, treating the hypotheses proposed & developed successfully by Newton, Einstein, Heisenberg, etc., as final and inviolable theories, just because they have been *working*, threaten the further evolution of human scientific minds (logics), and hence, the evolution of our sciences and technologies, and hence, eventually our very existence? Are we all suffering from the *Messiah Complex* so deep that we are irrecoverably believing that the final foundation for our *scientific edifice has already been firmly established*? Should we just stay focused on discovering only the right size *stones* to fit into the already established scientific edifice?

4. Applying IPM-E and the NIW-Principle to resolve the ambiguities

Once we have accepted the NIW-principle, then IPM-E dictates us to hold our final conclusions regarding the phenomenon we call *interference of light* before we have thoroughly

explored light-matter interaction processes and the impact of the quantum properties of detecting molecules during the process of photo electron emission (or electron transfer from valence to the conduction band). Obviously, we cannot simply sum the optical fields directly as we have been doing for centuries (Roychoudhuri 2010b, Roychoudhuri 2009a), albeit the fact that TF-FT, based on summation of fields, has been *working* and Maxwell's wave equation accepts any *linear combination* (sum) of harmonic waves as its solution, as $\vec{E}_{total}(t)$ shown below:

$$\vec{E}_{total}(t) = \vec{E}_1(t)\exp(i2\pi\nu_1t) + \vec{E}_2(t)\exp(i2\pi\nu_2t) + \dots + \vec{E}_n(t)\exp(i2\pi\nu_nt) \quad (3)$$

While the above equation may appear to be a mathematically correct representation of the physically superposed n-waves $\vec{E}_n(t)$, it is a logically wrong representation of physics because the mathematical operation sign "+" in physics represents an interaction mediated by some force of interaction; and there are no force of interaction between waves in the linear domain. We may create the convention of representing a physically superposed but non-interacting set of waves by using the semicolon sign as separator of different waves Roychoudhuri 2006a):

$$\vec{E}_{set}(t) \subset [\vec{E}_1(t)\exp(i2\pi\nu_1t); \vec{E}_2(t)\exp(i2\pi\nu_2t); \dots; \vec{E}_n(t)\exp(i2\pi\nu_nt)] \quad (4)$$

We can now give a better operational interpretation of the mathematical observation that Maxwell's wave equation can accept any linear combination of harmonic waves: Same volume of the vacuum or a noninteracting medium in the linear domain, can allow simultaneous presence and co-propagation of multiple EM waves. Let us now assume that we have introduced a photo detector within the physical volume of the superposed waves. Then each one of the E-vectors try to polarize the detecting molecules (or their clusters) and make them oscillate to the induced frequencies provided the intrinsic quantum properties of the molecules allow that. Let us use the symbol for this linear polarizability as ${}^1\chi(\nu)$, then the various stimulations can be represented as:

$$\vec{\psi}_n(t) \equiv \vec{d}_n(t) = [{}^1\chi(\nu)][\vec{E}_n] \Rightarrow {}^1\chi(\nu)E_n \quad (5)$$

The summation sign we use for superposition effect implies a process. Something has to carry out this process to keep the system causal. So the resultant stimulation can now be represented by Eq.6, while the summation, or the superposition effect is now carried out by the same dipole molecule (or their cluster) as they respond simultaneously and absorb energies from all the *quantum compatible* fields. A similar interaction relation can also be assumed for intra-cavity saturable absorbers:

$$\vec{\Psi}_{total}(t) = \sum_n \vec{\psi}_n = \vec{d}_1(t)\exp(i2\pi\nu_1t) + \vec{d}_2(t)\exp(i2\pi\nu_2t) + \dots + \vec{d}_n(t)\exp(i2\pi\nu_nt) \quad (6)$$

If the quantum transition bands of the detecting dipoles can respond simultaneously to only a subset of the frequencies from ν_p to ν_{p+r} , determined, say, by the band widths and the band gap of a solid state detector (or, a saturable absorber), then the effect of only these superposed waves will be experienced by the detector. Normally, the rest of the waves will remain unrecognized by the detector. The terms within the curly bracket below corresponds to the total resultant stimulations experienced by the detector belonging to the *quantum compatible* frequencies. To underscore the NIW-principle, we are showing the other superposed waves, outside the curly bracket and without the summation signs, since there are no interaction between these waves.

$$\bar{\Psi}_{total}(t) = \bar{E}_1(v_1, t)e^{i2\pi v_1 t}; \dots \left\{ \bar{d}_p(v_p, t)e^{i2\pi v_p t} + \bar{d}_{p+1}(v_{p+1}, t)e^{i2\pi v_{p+1} t} + \dots + \bar{d}_{p+r}(v_{p+r}, t)e^{i2\pi v_{p+r} t} \right\}; \dots \bar{E}_n(v_n, t)e^{i2\pi v_n t}. \quad (7)$$

For example, a silicon detector will not respond to either the high frequency (energy) X-ray or low frequency (energy) infra-red photons. The transformation experienced by the detector, or transfer of photo electrons from the valence to the conduction band due to energy transfer from all the *quantum compatible* fields to the photodetector, is given by the quantum mechanical recipe, the ensemble average of the square modulus of the effective complex amplitude stimulation:

$$D(t) = \langle \bar{\Psi}^*(t) \cdot \bar{\Psi}(t) \rangle \quad (8)$$

In reality, all frequencies, even those outside the *quantum compatible* band, stimulate the detecting dipoles accessing their nonlinear polarizabilities, however, normally the strengths of these nonlinear stimulations are very weak compared to the linear stimulations. The stimulations due to higher order polarizability terms are never zero in the real world:

$$\bar{\Psi}_{total}(t) = \sum_n^1 \chi(v) \bar{E}_n(t) e^{i2\pi v_n t} + \sum_n^2 \chi(v) \bar{E}_n^2(t) e^{i2\pi v_n t} + \dots + \sum_n^m \chi(v) \bar{E}_n^m(t) e^{i2\pi v_n t} \quad (9)$$

With these background, we can now approach to resolve the ambiguities, contradictions and paradoxes mentioned in Section 1.

4.1 Can superposed modes create a new mean frequency?

Readers are now requested to recall Section 2.1 and Fig.1 and Fig.2. IPM-E and the consequent NIW-principle tell us that the derivation of a *mean frequency* by mathematical summation of in-phase periodic frequencies in the linear domain is not a physical process that is allowed in nature. A saturable absorber placed inside a He-Ne laser, having the inhomeogeneously broadened gain medium, must always run at all the allowed longitudinal modes (Allen et al 1969). By virtue of the NIW-principle, these frequencies remain independent of each other even when their phases are locked with the help of cavity reverberation through the intracavity saturable absorber. The intensity absorbed by the saturable absorber, $I_{absrb.}$, is given by:

$$I_{sat.}(t) = \left| \sum_{n=0}^{N-1} \chi a e^{i2\pi(v_0 + n\delta v)t} \right|^2 = \chi^2 N^2 a^2 \frac{\sin^2 N\pi\delta v t}{\sin^2 \pi\delta v} \quad (10)$$

The absorber simply behaves as a fast temporal gate and, of course, the absorption efficiency rapidly enhances as the various modes become phase locked, which, in turn, makes the width of the individual modes much narrower than those in a free running CW laser (see Fig.3c). However, for a hohmogeneously broadened gain medium like Ti-Sapphire, there is no *locking of modes* since the gain medium tends to run at the gain line center under steady pulsing conditions (see Fig.1b). Accidental in-phase spontaneous emissions around the gain line center triggers the saturable absorber to start functioning as the required time-gating device. The readers should note that except for a constant factor χ^2 representing the linear polarizability of the saturable absorber molecules, this Eq.10 looks identical to the Eq.2, which we have been using to justify the *mode lock* hypothesis, as summation of modes, to be

a correct one! Working mathematics may confuse us, but a systematic application of IPM-E will direct us in the right direction.

4.2 Can a homogeneously broadened gain medium oscillate in all the allowed cavity modes?

Readers are requested to recall the discussion in Section 2.2. In general, a steadily oscillating laser with homogeneously broadened gain medium will always run at the gain line center (Siegman 1986), unless an intra-cavity device flattens the gain line envelop. Note that broader the gain bandwidth, shorter is the atomic life time and hence faster the lasing atom can recycle itself to contribute energy by stimulated emission in the next pulse. Only during the transient oscillation periods, as the laser is repetitively Q-switched, can one observe the presence of multiple longitudinal modes due to transient competitions enhanced by the presence of strong spontaneous emissions at all allowed frequencies. Of course, if the medium develops many defect centers, effectively creating *inhomogeneous* gain regions, one can also observe the presence of multiple longitudinal modes. And an excellent example is the case of a Q-switched diode laser, essentially homogeneously broadened, which we are analysing in Section-2.6 and 4.6 (see Fig.5a). But a well stabilized and periodically pulsing laser will always select the frequency at the highest gain point, which can be tuned by inserting an intra-cavity frequency tuner that introduces preferential losses over the entire gain line except around the desired frequency. This is why the *heroic* measurement of the carrier frequency of a *mode locked* Ti-Sapphire laser shows a unique carrier frequency under the pulse envelope (Fig.1b).

4.3 Can the time-frequency Fourier theorem be a principle of nature?

Readers are requested to recall the discussion in Section 2.3. The time-frequency Fourier theorem (TF-FT) is a very useful and a self-consistent mathematical theorem, however, by virtue of the NIW-principle, it cannot represent superposition of EM waves unambiguously in the most general sense. Further, it certainly does not model the physical process of light-matter interaction processes in the mathematical form generally presented in books. However, we have been effectively using the TF-FT as if it is a principle of nature as it is capable of predicting the correct measured data, except for a *constant*, the polarizability of the detecting dipole by the incident electric vector. While the TF-FT has been a very successful mathematical tool in most of the branches of physics, it incorrectly implies field-field interaction:

$$a(t) = \int_0^\infty \tilde{a}(f) \exp[i2\pi ft] df; \quad \tilde{a}(f) = \int_0^\infty a(t) \exp[-i2\pi ft] dt \quad (11)$$

Let us take a particular example to illustrate our point. Consider a two-modes, CW He-Ne laser beam of equal amplitude, passing through a Michelson interferometer (Michelson, 1962; the discoverer of the Fourier transform spectroscopy). Each mode will send two beams with a fixed phase delay on the detector that will experience the simultaneous presence of four beams (Roychoudhuri 2006b):

$$\begin{aligned} D(\tau) &= \left| \chi e^{i2\pi\nu_1 t} + \chi e^{i2\pi\nu_2 t} + \chi e^{i2\pi\nu_1(t+\tau)} + \chi e^{i2\pi\nu_2(t+\tau)} \right|^2 \\ &= \chi^2 \left| e^{i2\pi\nu_1 t} + e^{i2\pi\nu_1(t+\tau)} \right|^2 + \chi^2 \left| e^{i2\pi\nu_2 t} + e^{i2\pi\nu_2(t+\tau)} \right|^2 \\ &= \chi^2 [4 + 2(\cos 2\pi\nu_1 \tau + \cos 2\pi\nu_2 \tau)] \end{aligned} \quad (12)$$

As per Michelson's assumption, light beams corresponding to different optical frequencies are *incoherent* and hence they do not *interfere*. Accordingly, in the second step of Eq.12, we have applied the square modulus operation on each pair of terms separately corresponding to the two different frequencies. Note that the application of this correct but *arbitrary* mathematical logic depends upon the *incoherency* hypothesis. As per Michelson, one then extracts the oscillatory part of the data, after discarding the DC part. Application of the mathematical Fourier transform operation then yields the extraction of the source *spectrum*:

$$\begin{aligned} D_{Osc.}(\tau) &= \cos 2\pi\nu_1\tau + \cos 2\pi\nu_2\tau \\ \text{Or, } \tilde{D}(\nu) &= \delta(\nu - \nu_1) + \delta(\nu - \nu_2) \end{aligned} \quad (13)$$

Michelson's assumption of *incoherence* between frequencies were observationally correct as he could only use very slow optical detectors, slow eyes and photographic plates available in those days. He also incorrectly assumed light beams interfere by themselves to create energy re-distribution (fringes). Scrutinizing Eq.12 reveals why his summing the fields and our summing the dipole stimulations give identical results, except for a constant multiplying factor. This is because the mathematical logic allows us to take the common constant in an equation out of all terms and place it as a common multiplier. This is good enough for MDM-E driven science, but because of the application of this mathematical logic, we have lost sight of the real interaction process for centuries. Further, since the discovery of fast optical detectors, we know that different optical beams corresponding to different frequencies are really not *incoherent* and they give rise to heterodyne difference (beat) frequencies. We now have a new tool, called heterodyne spectroscopy:

$$\begin{aligned} D_{osc}(t, \tau) &= {}^1\chi^2 \left| e^{i2\pi\nu_1 t} + e^{i2\pi\nu_2 t} + e^{i2\pi\nu_1(t+\tau)} + e^{i2\pi\nu_2(t+\tau)} \right|^2 \\ &= {}^1\chi^2 [4 + 2\cos 2\pi(\nu_1 - \nu_2)t + 2[\cos 2\pi(\nu_1 - \nu_2)(t + \tau) \\ &\quad + \cos 2\pi\{(\nu_1 - \nu_2)t + \nu_1\tau\} + \cos 2\pi\{(\nu_1 - \nu_2)t - \nu_2\tau\}] \\ &\quad + 2{}^1\chi^2 [\cos 2\pi\nu_1\tau + \cos 2\pi\nu_2\tau]. \end{aligned} \quad (14)$$

Note that in the above Eq.14, if we have a slow detector, or a an electric circuit with a long LCR time-constant, the time dependent terms will average out to zero leaving behind the DC term of Michelson and we will be left with what Michelson's photographic plate would have registered, which is same as the final result of Eq.12. The readers should now appreciate that application of IPM-E and the NIW-principle are critical tools for developing working engineering principles behind optical instruments.

It is customary to expect new predictions from new principles. The prediction of the NIW-principle is that neither Fourier synthesis, nor Fourier decomposition can take place in the domain of optical frequencies where the detection is carried out by quantized atoms, molecules or their assemblies, as in solid state detectors. We have validated these predictions through two separate experiments. In the first experiment (Lee & Roychoudhuri, 2003; Lee, 2004), we have superposed two phase-stable optical beams with two different optical frequencies 2GHz apart and exactly bisecting one of the fine-structure Rb-resonance line. The Rb-atoms could not respond to these collinear beams since both the frequencies were outside their quantum stimulation boundary, which proves that Fourier synthesis to generate a new average frequency did not take place. When we tuned either one of these

two frequencies matching the actual Rb-resonance line, strong resonance fluorescence was clearly observable.

In the second experiment (Roychoudhuri and Tayahi 2006), we demonstrated that optical detectors cannot respond to Fourier decomposition frequencies corresponding to the envelope of a pulse. We carried out a heterodyne experiment by mixing the beam from a stable external-cavity CW diode laser beam with a steady pulse train derived from a separate Bragg-grating-stabilized diode laser but after the beam was amplitude modulated by an external LiNbO₃ modulator. The main heterodyne line remained unaltered whether the second laser beam was modulated or kept CW, proving that photodetectors cannot respond to Fourier frequencies corresponding to the pulse envelope. Of course, when the second diode beam was modulated, an oscillatory current corresponding to the modulation frequency was separately observable, besides the unaltered heterodyne beat frequency. The broader implications of using TF-FT as a principle of nature in the field of classical and quantum optics has been summarized in (Roychoudhuri, 2009a; 2007b); and earlier realization of the concept can be found in (Roychoudhuri, 1976).

4.4 Why regular CW He-Ne lasers show mode-lock-like pulsations?

Readers are now requested to recall the discussion in Section 2.4 and Fig.3 where an ordinary He-Ne laser appears to behave like a *mode locked* laser. Such a deceptive behavior from a He-Ne laser is all the more reason to apply IPM-E to detection processes and then appreciate that the conventional mode locking assumption behind the physical pulsation of a laser is incorrect. In a CW He-Ne laser, as per the NIW-principle, each mode oscillate independent of the others, but naturally with phases that remain steady relative to each other for periods of milliseconds or longer due to very high-Q cavity (high reflective cavity mirrors). So, when a multimode He-Ne beam stimulates a fast detector, its resultant *coherent amplitude* stimulation can be described for intervals of milliseconds as:

$$d(t) = \sum_{n=0}^{N-1} \chi e^{i2\pi(v_0 + n\delta v)t} \approx \chi \frac{\sin N\pi\delta vt}{\sin \pi\delta vt} e^{i2\pi v_0 t} \quad (15)$$

Eq.15 is identical to Eq.1 except for the multiplicative constant χ representing the linear polarizability of the detecting molecules. The temporal variation in the detector current, when normalized, is given by:

$$D(t) = |d(t)|^2 = (\chi^2 / N^2) [\sin^2 N\pi\delta vt / \sin^2 \pi\delta vt] \quad (16)$$

With a fast oscilloscope trace, using *internal trigger signal*, as is the case for Fig.3b, one will naturally observe *mode-lock-like* oscillation in the detector current. For a quantitative computational match, one needs to set $N=5$ in Eq.16 and adjust the intensities of the five modes as per the spectrum in Fig.3a.

The self-heterodyne lines of Fig.3d can also be appreciated by re-deriving the detector current in a different trigonometric form, as shown as in Eq.17, and then isolate the oscillatory term from the DC term, as in Eq.18:

$$D(t) = d^*(t)d(t) = \frac{\chi^2}{N} + \frac{2\chi^2}{N^2} \sum_{p=1}^{N-1} (N-p) \cos[2\pi p\delta vt] \quad (17)$$

$$D_{osc}(t) = \frac{2^1 \chi^2}{N^2} \sum_{p=1}^{N-1} (N-p) \cos[2\pi p \delta \nu t] \quad (18)$$

It is the electronic design of an ESA to display the oscillatory current in terms of sum of harmonic terms, as in Eq.18. Again, the *internal sampling time constant* must be set at about a millisecond or less (He-Ne laser coherence time). For $N=5$, we should have four harmonic lines with difference frequencies at $\delta \nu$, $2\delta \nu$, $3\delta \nu$ and $4\delta \nu$, as can be seen in Fig.3c around the central *zero frequency* line (Lee 2004; Roychoudhuri et al 2006).

4.5 Is synthetic mode locking possible?

Readers are now requested to recall discussions in Section 2.5 and Fig.4. Again, by virtue of the NIW-principle, it is not possible to generate oscillatory light energy simply by superposing phase-stable CW light beams with a periodic frequency difference in free space. However, based on the observation and analysis of section 4.4, it is clear that one can always generate *pulsating response out of a material medium* whose energy absorbing dipoles can respond to all the frequencies simultaneously and can recycle their measurable transformation with the required high speed (Lee 2004; Roychoudhuri et al 2006). If the phase locked multi-frequency source has a pulse envelope $a(t)$, the measured width will be narrower than $a(t)$ squared. *If the detector response time is slower than the periodicity $\tau = (1 / \delta \nu)$ implied by the Eq.16, the observation will not corroborate a mode-lock-like behavior (periodic pulsation of energy).*

4.6 Can autocorrelation data unambiguously determine the existence of ultrashort pulses?

Readers are now requested to recall the discussion in Section 2.6 and Fig.5. There we have shown that a Q-switched diode, with a built-in saturable absorber was able to generate 12ps pulse for each Q-switching current pulse. But the autocorrelation trace (Fig.5b and c) showed 94fs pulse train within each 12ps Q-switched pulse. Are these fs spikes artifacts of measurement process, or the laser is really partially *mode locked*? The author believes that they are artifacts of measurement and product of very strong nonlinear second harmonic energy conversion due to high-visibility fringes as the path delay changes by the cavity round-trip delay in the non-collinear second harmonic-generation interferometer. In such an interferometer the laser beam is replicated into two beams and then superposed with a variable path delay.

People who are familiar with two-beam interferometry or holography using a CW multimode laser to achieve unit visibility fringes, they must set the relative path delay between the two beam exactly as $n\tau$ (integral multiple of cavity round trip time). Fig.6 below shows the computer plot of two-beam fringe visibility, or the modulus of the autocorrelation function, using the longitudinal mode spectrum (without the background pedestal) shown in Fig.5a.

Amplitude of the second harmonic generation is proportional to the intensity of the stimulating signal and hence the recorded intensity in the non-collinear 2nd harmonic signal (autocorrelation spikes of Fig.5b & c) is proportional to the square of the fringe visibility function shown in Fig.6, and hence they are even narrower than these visibility peaks. As mentioned in Section 2.6, the existence of a true ~ 100 fs pulse would imply a registered spectral broadening of 10,000 GHz. But our spectrum consists of about 32 individual lines of half-width 83.3 GHz wide over a pedestal of approximately 1,300GHz half-width, not 10,000GHz! We believe that the pedestal represents the broad spontaneous emission, real carrier frequencies across the entire gain bandwidth, rather than an instrumental spectral broadening due to a 100fs laser pulse.

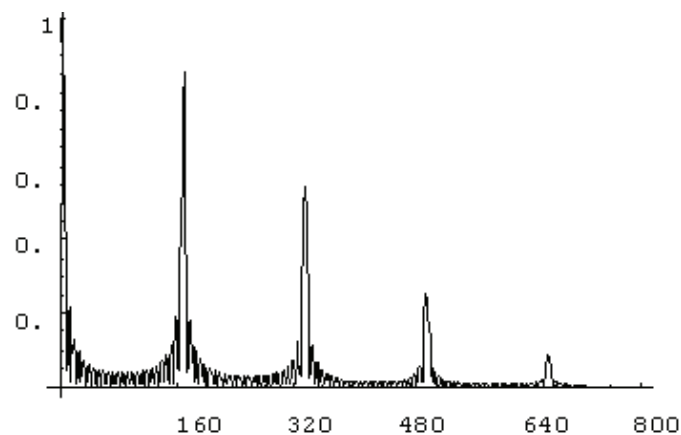


Fig. 6. Computer simulation of sharp but decaying fringe visibility due to superposition of two replicated beams produced from a beam containing 32 mode frequencies of Fig5a.

To further appreciate the arguments presented here, we need to re-formulate foundational mathematical relations for spectrometry. Attempts to visualize the processes behind recorded data (measured transformations in detectors), will reveal further roots behind some of the misconceptions and ambiguities discussed above.

4.6.1 Generalized formulation of spectral fringe broadening.

We will now derive formulations to distinguish between apparent spectral fringe broadening due to a pulse carrying a single carrier frequency and multiple carrier frequencies under the same temporal envelope. But, let us first justify this attempt by underscoring the paradox built into the classical formulation of spectrometry. Classical spectrometry is formulated based on propagating a CW *monochromatic* beam $\exp[-i2\pi\nu_0 t]$ that has a constant amplitude and a unique carrier frequency existing over all time, which cannot exit in the real world as it would contain infinite energy and violate the law of conservation of energy. For a grating with N-slits and a step delay τ , the classical approach derives a spectral fringe of a finite width, $\delta\nu = (1/N\tau)$ (Born & Wolf, 1980), instead of a *delta function* $\delta(\nu - \nu_0)$:

$$I_{cw}(\nu, \tau) = \left| \sum_{n=0}^{N-1} (1/N) e^{-i2\pi\nu\tau} \right|^2 = \frac{1}{N^2} \frac{\sin^2 N\pi\nu\tau}{\sin^2 \pi\nu\tau} \equiv \frac{1}{N} + \frac{2}{N^2} \sum_{p=1}^{N-1} (N-p) \cos[2\pi p\nu_0\tau] \quad (19)$$

Then it appropriately identifies that this fringe width $\delta\nu$ does not correspond to the physical presence of any new carrier frequencies, rather it is an instrumental artifact, defined as the *instrumental CW response function*, which we must deconvolve from experimental spectral fringes to extract actual *spectrum*. However, when a pulsed light beam generates a spectral fringe, we automatically assume that it represents the real pulse spectrum (or, real frequency content) and the broadening is due to Fourier spectrum that a pulse *inherently* contains. This conjecture is based upon the assumption that the TF-FT is a functional principle in nature, which we have argued against in this and the last sections. In the next few paragraphs, we will derive the most general spectrometer response function due to a time-finite pulse, $a(t)\exp[-i2\pi\nu_0 t]$, that has a unique carrier frequency. We will propagate this carrier frequency and the envelope function through spectrometer directly, instead of the Fourier spectrum of the pulse envelope existing over all time.

Let us now apply our IPM-E and the NIW-principle to optical spectrometers. From the standpoint of IPM-E, spectrometers like gratings and Fabry-Perots are *linear* pulse replicators; they function as wavefront dividers (as in an N-slit grating) and amplitude dividers (as in a Fabry-Perot interferometer of finesses $\sim N$), respectively. These *linear* beam replicating devices cannot generate new optical frequencies out of the incident beam, irrespective of the length of the pulse (fs or infinite CW). Further, according to the NIW-principle, these replicated beams *do not interfere* or interact with each other by themselves to create new energy distribution (fringes). The optical components associated with the spectrometers physically superposes the replicated beam-train with a periodic time delay on a detector, which then registers a transformation according to its absorbed energy distribution determined by the actual carrier frequencies. Each spectral line will have the same instrumental line broadening determined by the common incident pulse envelope. We will consider here the case of a grating only. For details of derivations and other implications in the field of optics, the interested readers should consult the following references (Roychoudhuri & Tayahi 2006; Roychoudhuri 2004; Roychoudhuri et al 2003). For the purpose of easy illustration, we are considering only a transmission blazed grating with four steps. It replicates the incident pulse into N periodically delayed pulses with a step delay of τ as shown in Fig.7.

We define the total time delay between the first and the N-th replicated pulse as the spectrometer time constant, τ_0 , which connects with the classical definition of resolving power $R=mN$ as shown below in Eq.20. For a grating working in the m-th order, we can write:

$$\tau_0 = N\tau = N.(m\lambda / c) = R\lambda / c = R / \nu \quad (20)$$

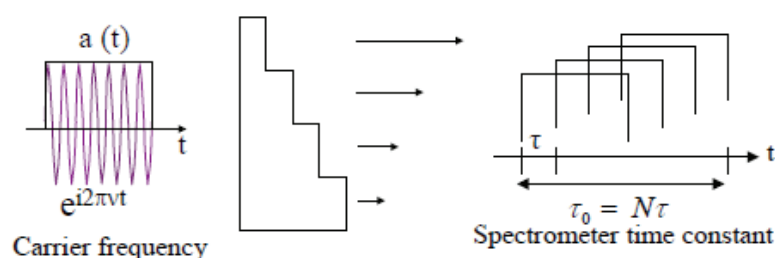


Fig. 7. Generation of a train of N pulses from a single incident pulse by an N-slit grating with a periodic delay of τ . In a spectrometer this train of partially overlapped pulses are superposed on a detector whose response generate the spectrometer fringes (from Roychoudhuri et al, 2003).

From the view point of *mapping the process behind spectrometer fringe evolution*, τ_0 plays a critical role in spectrometry, to be apparent later, which was never explicitly appreciated in classical spectrometry. The normalized dipolar amplitude stimulation of the detector at the output of the spectrometer can be given by:

$$d_{\text{det}}(t, \nu_0) = \sum_{n=0}^{N-1} (\chi / N) a(t - n\tau) \cdot \exp[i2\pi\nu_0(t - n\tau)] \quad (21)$$

The detector then generates fringes by absorbing energies dictated by the relative delays in the superposed pulse train determined by $n\nu_0\tau$:

$$D_{\text{det}}(t, \nu_0) \equiv |d_{\text{det}}(t, \nu_0)|^2 = \left| \sum_{n=0}^{N-1} (\chi / N) a(t - n\tau) \cdot \exp[i2\pi\nu_0(t - n\tau)] \right|^2 \quad (22)$$

A ps streak camera will display an apparent spectral fringe whose width will vary in time as per Eq.22. We certainly should not interpret this time varying fringe width as time evolving spectrum! Note that the case of temporally chirping spectrum is not modeled by Eq.22. If the detector energy is integrated over a duration longer than that of the entire pulse train, which ordinary spectrometers do, then we have:

$$I_{pls}(\nu_0, \tau) = \int D_{\text{det}}(\nu_0, t) dt = \int dt \left| \sum_{n=0}^{N-1} \left(\frac{1}{N} \chi \right) a(t - n\tau) \cdot \exp[i2\pi\nu_0(t - n\tau)] \right|^2 \quad (23)$$

Now we get time integrated fringe pattern as the *pulse-response-function* for a single carrier frequency,

$$I_{pls}(\nu_0, \tau) = \frac{1}{N} \chi^2 + \frac{2}{N^2} \chi^2 \sum_{p=1}^{N-1} (N-p) \gamma(p\tau) \cos[2\pi p\nu_0\tau] \quad (24)$$

Where, $p \equiv |n - m|$ and the autocorrelation factor $\gamma(p\tau)$ is defined by:

$$\gamma(p\tau) = \int d(t - n\tau) d(t - m\tau) dt / \int d^2(t) dt \quad (25)$$

If there are many carrier frequencies with a normalized intensity function $b(\nu)$ under the same pulse envelope $a(t)$, as is the case discussed for a Q-switched diode laser in Fig.6, then the time integrated fringe spectrum should be represented by the convolution:

$$I_{\text{mult.freq.}}(\nu, \tau) = b(\nu) \otimes I_{pls}(\nu, \tau) \quad (26)$$

Let us now bring connections to classical spectrometric results. When the pulse width δt is much greater than the spectrometer time constant τ_0 , say, $\delta t \geq 10\tau_0$, then the overlap between all the replicated pulses will be approximately complete and hence all the autocorrelation factor $\gamma(p\tau)$ will be close to unity for all values of p . Then using Eq.24 and 25, we can write:

$$\lim_{\substack{Lt. \\ \gamma \rightarrow 1 \\ \delta t > 10\tau_0}} I_{pls}(\nu_0, \tau) = \frac{1}{N} \chi^2 + \frac{2}{N^2} \chi^2 \sum_{p=1}^{N-1} (N-p) \cos[2\pi p\nu_0\tau] \equiv \frac{1}{N^2} \frac{\sin^2 \pi N\nu_0\tau}{\sin^2 \pi \nu_0\tau} = {}^1\chi^2 I_{cw}(\nu_0, \tau) \quad (27)$$

Thus, for a pulse of width δt that is much longer than the time constant of a spectrometer $\tau_0 = R\lambda / c$, our time-domain formulation converges identically to the classical result, except for the characteristic detector polarizability constant ${}^1\chi^2$. After recovering the classical *monochromatic-beam-result*, we would like to underscore that our *pulse-response-function* $I_{pls}(\nu, \tau)$ of Eq.24 can also be expressed, using Parseval's energy conservation theorem (Roychoudhuri et al 2003), as a convolution between the classical *CW-response-function* and the normalized Fourier intensity spectrum $\tilde{A}(\nu)$, the normalized square modulus of the Fourier transform of $a(t)$:

$$I_{pls}(\nu, \tau) \approx \int_{-\infty}^{\infty} |d_{\text{det}}(t, \nu)|^2 dt = I_{cw}(\nu) \otimes \tilde{A}(\nu) \quad (28)$$

It is now obvious that the *apparent* spectral fringe broadening due to a pulse carrying a single carrier frequency, can be *thought of* as that due to the Fourier frequencies obtainable by applying the TF-FT on the pulse envelope. One can now appreciate why $I_{pls}(\nu_0, \tau)$ is generally considered to be the response due to a *transform limited pulse*; it is the spectrometer response due to a pulse with a single carrier frequency! However, this energy distribution in the broadened fringe $I_{pls}(\nu_0, \tau)$, or the width $\delta\nu$ of the *pulse response function*, must not be considered as due to the presence of many real physical frequencies; they correspond to the energy spread from the same carrier frequency ν_0 . Based on the Fourier convolution relation of Eq.28, the bandwidth product $\delta\nu\delta t \approx 1$ (*time-frequency uncertainty* or the *bandwidth limit*) appears to be working! However, the extra broadening of the grating fringe is due to *partial overlap* of the train of finite pulses (see Fig.7). It has physically nothing to do with the time-frequency uncertainty relation; it is just a mathematical coincidence. The width of the fringe is a joint artifact of the instrument and the pulse envelope function $a(t)$.

This is one more example on how to appreciate the power of IPM-E over MDM-E in correctly identifying the real interaction processes that go on in nature to generate measurable data. While MDM-E makes us draw wrong physical conclusions, IPM-E guides us to extract out the correct interaction process behind spectrometers; they are just *linear pulse replicators*! Successes achieved through *curve-fitting* mathematical formulations makes us believe that TF-FT is a principle of nature; but it is not. We should consider the distribution of energies corresponding to the presence of real physical carrier frequencies as the physical spectrum, $b(\nu)$ of Eq. 26. $A(\nu)$, the square modulus of the Fourier transform of the pulse envelope function $a(t)$, does not represent any physical frequencies.

5. Summary

We have given six concrete cases of laser pulse parameters for which standard text books give ambiguous or incorrect physical interpretations of laser pulse characteristics based on the century old premise that light beams *interfere* (interact) and regroup their energy by themselves. We have presented a better methodology of thinking, the Interaction Process Mapping Epistemology (IPM-E). IPM-E helps us use our creative human logics, while leveraging our mathematical logics, to access a better glimpse at the unknown cosmic logics. But we need to refine that *glimpse* into a more and more accurate representation of the cosmic logics by relying upon refining the map of the various interaction process through repeated and iterative *visualization* of many related interaction processes through as many diverse observations as possible.

IPM-E helped us recognize the universal NIW-principle (Non-Interaction of Waves). Application of this NIW-principle resolves all the conceptual ambiguities identified in this chapter. In the process, we recognize that the key principle behind short pulse generation is essentially the insertion of an intracavity device whose transparency to the intracavity intensity can switch back and forth within the shortest possible time interval. This is why a properly arranged Kerr-medium, undergoing non-linear intensity dependent refractive index change as a *bulk medium*, makes the switch faster than saturable absorbers that goes through the quantum mechanical steps of excitation and de-excitation to create the oscillatory time gate. The concept of *mode locking* is only partially useful.

The fundamental science and the related technologies behind the field of ultra short pulse laser can advance much faster once we explicitly recognize that a reality based methodology of thinking, like IPM-E, is a much more powerful tool than the curve fitting methodology, like MDM-E. This is because IPM-E builds upon MDM-E while guiding us to search deeper into nature's reality. We must not forget that we can only discover cosmic logics and laws, not invent them. We can invent technologies by employing cosmic logics provided we have already discovered them. The best approach to get closer to cosmic logics is to keep on refining the map of interaction processes as they are more evident to our imaginations than our capacity to directly access the cosmic logics using only MDM-E.

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