Application of Graded-Index Plastic Optical Fiber in broadband access networks

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1. Introduction

The explosive growth of broadband multimedia applications, such as video streaming, high-definition television (HDTV), video on demand, and interactive games, a huge demand for bandwidth has been imposed on the access infrastructure. The next generation access solutions have to be cost efficient to provide huge bandwidth. However, to gain this bandwidth usually needs high performance and high cost optical and electrical components. To reduce the cost is the main motivation for researchers, carriers and equipment providers. Fortunately, people have found some good solutions. Specially, newly developed plastic optical fiber (POF) has been demonstrated that it can be used to provide huge bandwidth and low insertion loss by some special design. Recently, graded index POF (GI-POF) has demonstrated that it can provide over 40GHz banwidth. Some advanced modulation formats can also be employed to extend the bandwidth of the GI-POF further. Directly modulated laser with special optical filtering technique can generate a laser to increase the dispersion tolerance and extend the transmission distance of signal in GI-POF. Optical orthogonal frequency division multiplexing signal (OFDM) can be used to transmit signal in narrow bandwidth so that it can be also used to increase the bandwidth of the GI-POF. In this chapter, we will review these new techniques and report our lastest results.

2. Access optical network

Access networks connect business and residential premises to metropolitan area networks (MANs) or wide area networks (WANs). Because of the explosive growth of broadband multimedia applications, such as video streaming, high-definition television (HDTV), video on demand, and interactive games, a huge demand for bandwidth has been imposed on the access infrastructure. As DWDM technology was developed for the long haul network and gigabit Ethernet for the local area network (LAN), access networks tend to be the bottle neck for end-to-end broadband applications. Today, the two most popular access network solutions are digital subscriber loop (xDSL) technologies deployed by telephone companies, and cable modems from cable companies. These access technologies do not have comparable bandwidth capability with Gigabit Ethernet and have limitations in providing high quality integrated services, including video, voice, and data. Unlike metro and long-haul networks, access networks must serve a more diverse and cost sensitive customer base. End users may range from individual homes, to corporate premises, to hotels, and services must therefore be provisioned accordingly. Data, voice, and video must be offered over the same high-speed connection with guarantees on quality of service (QoS), and the ability to upgrade bandwidth and purchase content on a needed basis. Therefore, the next generation access solutions have to be cost efficient when providing more bandwidth.

In the so-called FTTx access networks, optical fiber replaces copper in the distribution network. For example, in fiber to the curb (FTTC) or home (FTTH), the capacity of access networks is sufficiently increased to provide broadband services to subscribers. Because of the cost sensitivity of access networks, passive optical networks (PONs) are considered to be the most promising technology as they can provide reliable yet integrated data, voice, and video services to end users at bandwidths far exceeding current access technologies. Unlike other access networks, PONs are point to multipoint networks capable of transmitting over 20 kilometers of single mode fiber. PONs can offer symmetrical data transmission on both the upstream and downstream links, allowing the end user to provide Internet services such as music file sharing and Web hosting. In addition to providing a good alternative, PONs represent an excellent evolutionary path for current access technologies such as cable and DSL. By using passive components (such as optical splitters and couplers) and eliminating regenerators and active equipment normally used in fiber networks, PONs reduce the installation and maintenance costs of fiber as well as connector termination space. These costs still require laying fiber, which makes PONs more expensive to install. However, since fiber is not bandwidth limited but loss limited (as opposed to copper wires, cable, and wireless), the potential performance gains and long-term prospects make PONs well-suited for new neighborhoods or installations.

PONs typically fall under 2 groups: ATM PON (APON) and Gigabit PON (GPON) from Full Service Access Network (FSAN) and the International Telecommunication Union – Telecommunication Standardization Sector (ITU-T); and Ethernet PON (EPON) from IEEE 802.11ah Ethernet in the first mile (EFM) working group. In the APON and BPON specifications, ATM is used as the native protocol data unit (PDU), which implies protocol conversion between Ethernet and ATM is needed. EPON combines low-cost Ethernet equipment and low cost passive optical components, and has therefore attracted more attention in recent years.

Current access technologies represent a significant bottleneck in bandwidth and service quality between a high-speed residential/enterprise network and a largely overbuilt core backbone network. Backbone networks are provisioned for operation under worst-case scenarios of link failures, and thus backbone links are lightly loaded most of the time. In addition, high capacity routers and ultra-high capacity fiber links have created a true broadband architecture. However, large backbones are not the whole the equation; distribution of that connectivity to individual enterprises and homes is just as critical for meeting the huge demand for more bandwidth (Fig. 1). Unfortunately, the cost of deploying true broadband access networks with current technologies remains prohibitive. This in turn makes it difficult to support end-to-end Quality of Service (QoS) for a wide variety of applications, particularly non-elastic applications such as voice, video, and multimedia that cannot tolerate variable or excessive delay or data loss.

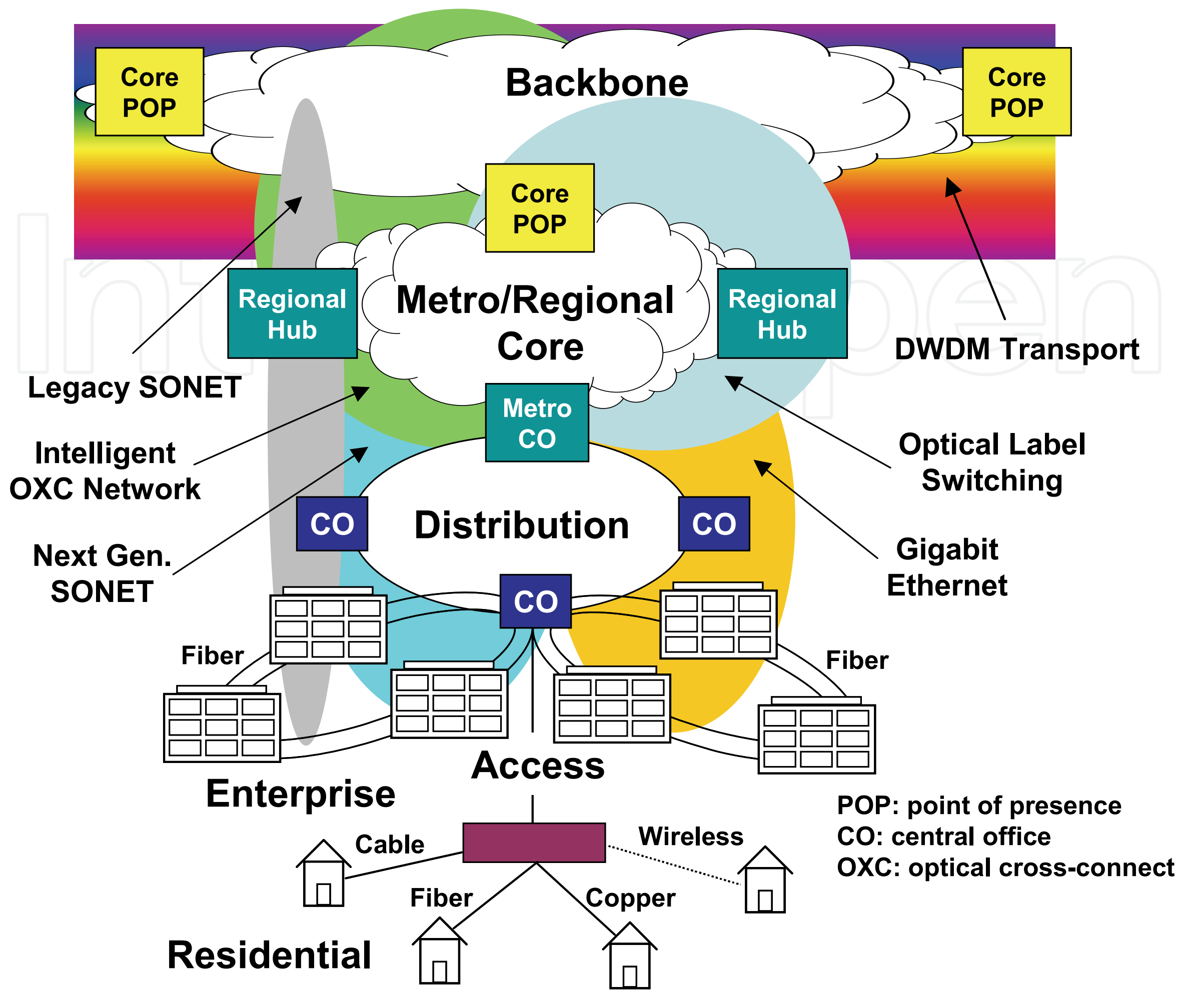


Fig. 1. Distributing optical backbone connectivity to enterprises and homes.

2.1 Existing Access Solutions

When it comes to access networks, network operators have a difficult choice among competing technologies – Digital Subscriber Line (DSL), cable, optical, and fixed wireless. Key considerations to the choice include deployment cost and time, service range, and performance. The most widely deployed solutions today are DSL and cable modem networks, which have a combined total of roughly 25 million users by the end of 2003. Although they offer better performance over 56 Kbit/s dial-up telephone lines, they are not true broadband solutions for several reasons. For instance, they may not be able to provide enough bandwidth for emerging services such as content-rich services, media storage, peer-to-peer services, multi-player games with audio/video chat to teammates, streaming content, on-line collaboration, high-definition video-on-demand, and interactive TV services. In addition, fast Web-page download still poses a significant challenge, particularly with rich, engaging, and value-added information involving high-resolution DVD video streaming, multimedia animation or photo quality images. Finally, only a handful of users can access multimedia files at the same time, which is in stark contrast to direct broadcast TV services. To encourage broad use, a true broadband solution must be scalable to thousands of users and must have the ability to create an ultra-fast Web-page download effect, superior to turning the pages of a book or flipping program channels on a TV, regardless of the content.

A major weakness of both DSL and cable modem technologies is that they are built on top of existing access infrastructures not optimized for data traffic. In cable modem networks, RF channels that are left over after accommodating legacy analog TV services are dedicated for data. DSL networks do not allow sufficient data rates at required distances due to signal distortion and crosstalk. Most network operators have come to realize that a new, data-centric solution is necessary, most likely optimized over the Internet Protocol (IP) platform. The new solution should be inexpensive, simple, scalable, and capable of delivering integrated voice, video, and data services to the end-user over a single network.

2.2 Ethernet for the First Mile

Ethernet for the First Mile (EFM) is an effort to extend Ethernet's reach over the first-mile access link between end-users and carriers, and make Ethernet a low-cost broadband alternative to technologies such as DSL and cable. The motivation for doing this is sound since there are currently over 500 million Ethernet ports deployed globally and it is advantageous to preserve the native Ethernet frame format rather than terminate it and remap its payload into another layer 2 protocol (e.g., Point-to-Point Protocol, PPP). The EFM specifications are developed by the IEEE 802.3ah Task Force (http://www.ieee802.org/3/efm), which was formed in November 2000. The draft standard (version 3.0 was issued on January 2004) includes *physical layer* specifications for copper, fiber point-to-point, fiber point-to-multipoint topologies. It is supported by the EFM Alliance or EFMA (www.efmalliance.org), a vendor consortium formed in December 2001 to:

- Promote industry awareness and acceptance of EFM standard;
- Contribute technical resources to facilitate standard development;
- Provide resources for multi-vendor interoperability.

2.3 Broadband Optical Access

DSL or cable-modem access provides benefits of installed infrastructure, virtually eliminating deployment costs. If fixed wireless access is chosen, network providers gain the benefit of quick and flexible deployment. However, these access methods may suffer bottlenecks in bandwidth-on-demand performance and service range. For example, cable networks are susceptible to ingress noise, DSL systems can be plaqued with significant crosstalk, and unprotected broadcast wireless links are prone to security breach and interference. Furthermore, current DSL and cable deployments tend to have a much higher transmission rate on the downstream link, which restricts Internet applications to mostly Web browsing and file downloads.

While wireless access is excellent for bandwidth scalability in terms of the number of users, optical access is excellent for bandwidth provisioning per user. Furthermore, the longer reach offered by optical access potentially leads to more subscribers. Optical access networks offer symmetrical data transmission on both the upstream and downstream links, allowing the end user to provide Internet services such as music/video file sharing and Web hosting. In addition to providing a good alternative, such networks represent an excellent evolutionary path for current access technologies. These costs still require laying fiber, which makes optical access networks more expensive to install. However, since fiber is not

bandwidth limited but loss limited (as opposed to copper wires, cable, and wireless), the potential performance gains and long-term prospects make optical access networks well-suited for new neighborhoods or installations. In addition, there are innovative solutions for deploying fiber in the last mile, even in established neighborhoods. For example, instead of investing in expensive dedicated fiber conduits, existing sanitary sewers, storm drains, waterlines, and natural gas lines that reach the premises of many end users can be exploited. Fiber can be housed in these utilities by forming creative business partnerships among optical fiber owners, service providers, utility pipe owners, vendors, and city municipalities.
Access networks should be scalable in bandwidth provisionable per-user. To be scalable with number of subscribers, it is highly important to identify architectures that allow low equipment cost per subscriber. As new applications appear and demand higher bandwidth, the network should be gracefully upgraded. It is important to be able to perform an incremental upgrade where only the subscribers requiring higher bandwidth are upgraded, not the entire network. Since the lifespan of optical fiber plant is longer compared to copper or coaxial cables, it is expected that the optical network will be upgraded multiple times during its lifetime. As such, it is important to design access architectures that allow seamless upgrade. In addition, the deployment of fibers between residences can be used to connect end-users directly, forming an autonomous communication network among residential end-users, thereby improving the overall service reliability through provision of redundant data paths similar to the multihop wireless architecture described in the previous section.

2.4 Passive Optical Networks

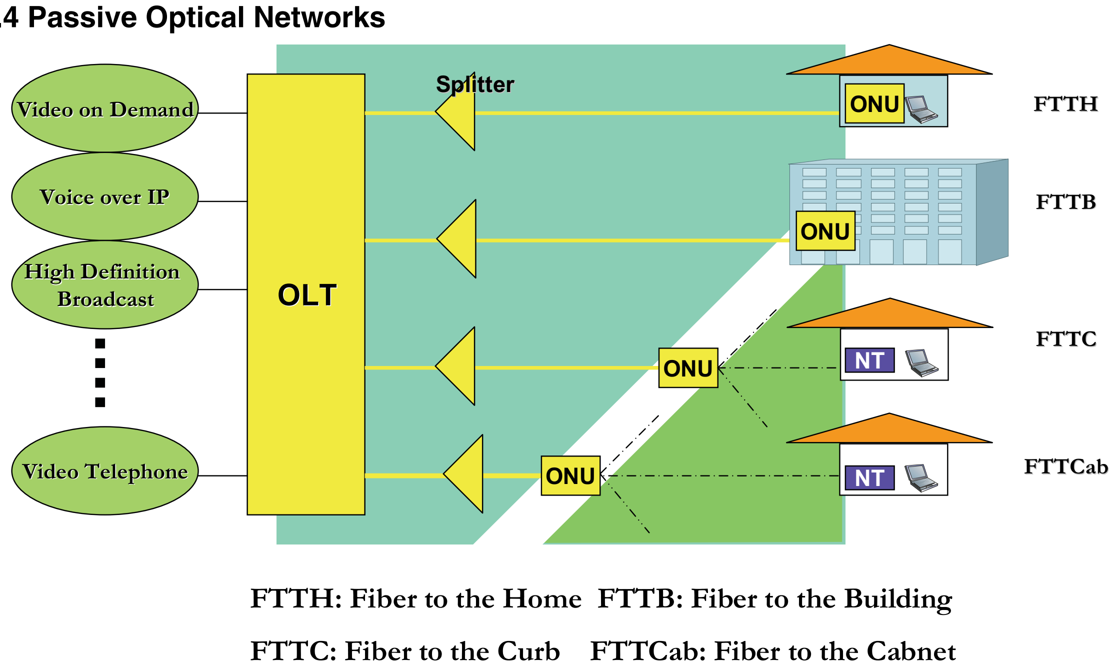


Fig. 2. Typical Passive Optical Access Network.

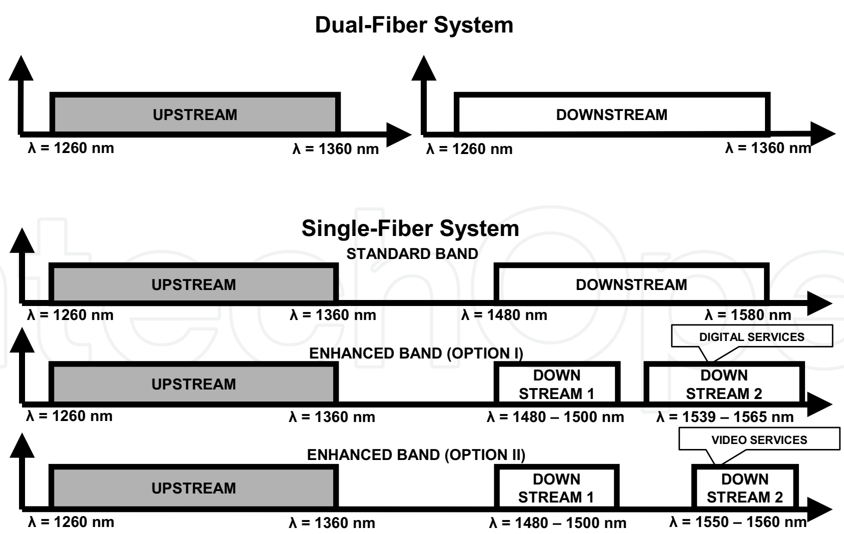


Fig. 3. Upstream and downstream optical bands for dual and single-fiber PONs.

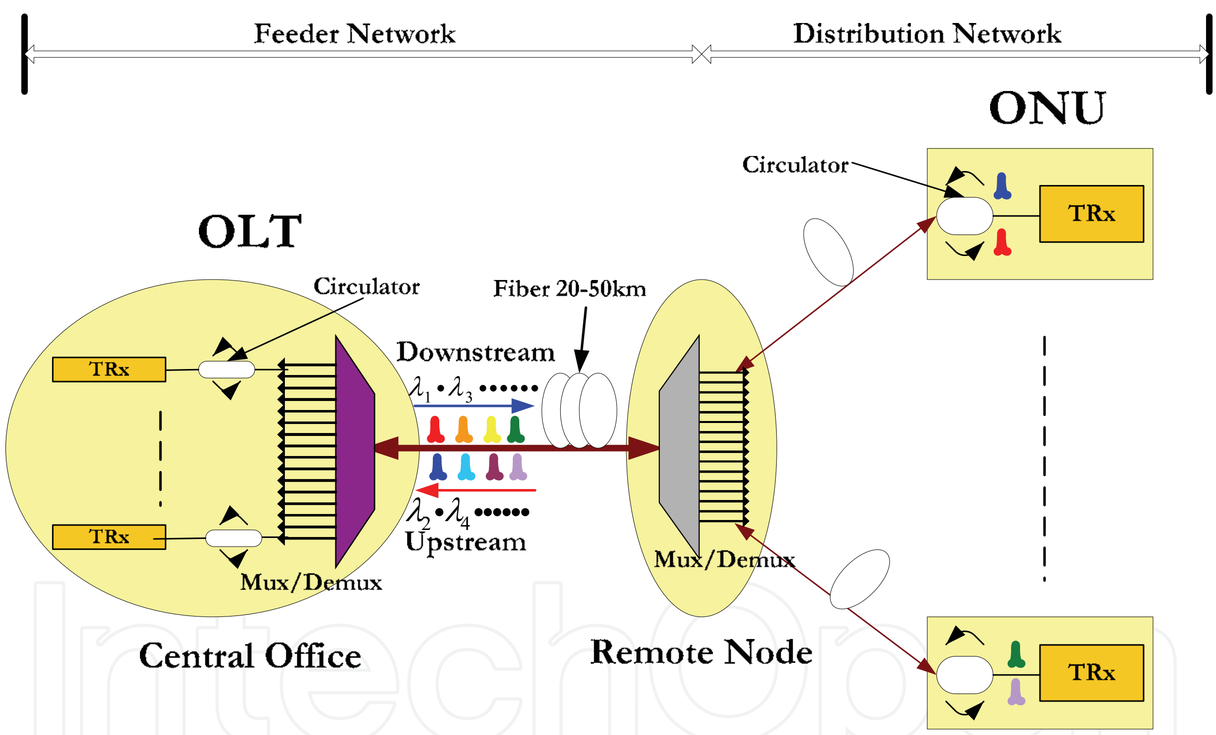


Fig. 4. The detailed architecture between OLT and ONU

Passive optical network (PON) is a technology viewed by many as an attractive solution to the last mile problem as PONs can provide reliable yet integrated data, voice, and video services to end users at bandwidths far exceeding current access technologies. Unlike other access networks, PONs are point to multipoint networks capable of transmitting over 20 kilometers of single-mode fiber. As shown in Fig. 2, a PON minimizes the number of optical transceivers, central office terminations, and fiber deployment compared to point-to-point and curb-switched fiber solutions. By using passive components (such as optical splitters and couplers) and eliminating regenerators and active equipment normally used in fiber networks (e.g., curb switches, optical amplifiers), PONs reduce the installation and maintenance costs of fiber as well as connector termination space. The general PON architecture consists of the Optical Line Terminator (OLT) on the service provider side and Optical Network Unit (ONU) (or sometimes the Optical Network Terminal) on the user side (Fig. 3). The ONUs are connected to the OLT through one shared fiber and can take different FTTx configurations e.g., Fiber to the Home (FTTH), Fiber to the Curb (FTTC), and more recently Fiber to the Premise (FTTP). The upstream and downstream optical bands specified by ITU-T for dual and single-fiber PONs are shown in Fig. 4.

PONs typically fall under two groups: ATM PONs (APONs) and Ethernet PONs (EPONs). APON is supported by FSAN and ITU-T due to its connection-oriented QoS feature and extensive legacy deployment in backbone networks. EPON is standardized by the IEEE 802.3ah Ethernet in the First Mile (EFM) Task Force. EPONs leverage on low cost, high performance, silicon-based optical Ethernet transceivers. With the growing trend of GigE and 10GigE in the metro and local area networks, EPONs ensure that IP/Ethernet packets start and terminate as IP/Ethernet packets without expensive and time consuming protocol conversion, or tedious connection setup.

2.5 Wavelength Division Multiplexing Optical Access

Wavelength Division Multiplexing (WDM) is a high capacity and efficient optical signal transmission technology that is prevalent in long-haul backbone applications, but is now emerging in Metropolitan Area Networks (MAN). WDM uses multiple wavelengths of light, each wavelength corresponding to a distinct optical channel (also known as lightpath or lamda, λ), to transmit information over a single fiber optic cable simultaneously. Current backbone commercial WDM systems have been increased up to 40 (100GHz spacing),80 (50GHz spacing) in C-band or 160 wavelengths in C+L-band on a single fiber. It is an economical alternative to installing more fibers and a means to dramatically provide higher capacity.

Current demand of bandwidth is nearly approaching the limit of transmission capacity of copper-based technologies like Digital Subscriber Line (DSL) or cable modem. Although based on aforementioned TDMA PON has the ability to provide up to 1-2.5Gb/s, burst mode reception at OLT and the clock synchronization of different ONUs have already been the main barrier to limit the TDMA mechanism up to higher signal rates. Therefore, WDM has been considered as a transition path from the current access technologies to the ultimate access solution. WDM itself inherits many advantages from the WDM technology of backbone or metro area such as large capacity, data transparent, multi-service, easy management, network security, and upgradability . And also combined the merits of PON network, WDM PON has been considered as future-proof ideal solution. Regarding the wavelength assignment for WDM PON, there are two choices: Coarse WDM (CWDM) or Dense WDM (DWDM). CWDM utilizes 18 wavelengths from 1270nm to 1610nm covering O, E, S, C, L-band with a wide channel spacing 20nm, therefore, athermal AWG and uncooled laser sources are good enough. Low cost is the most attractive advantage for CWDM. However, the elimination of strong absorption at the water peak in E-band and the need for effective all band amplification become the two critical issues that must be addressed in order to longer reach. On the other hand, DWDM achieves greater spectral efficiency using 50/100GHz channel spacing and with commercially available fiber-based

EDFA, can be scalable in distance and number of users, which makes it a better upgrade option in the long-term future.

WDM optical access is a future-proof last mile technology with enough flexibility to support new, unforeseen applications. WDM switching can dynamically offer each end user a unique optical wavelength for data transmission as well as the possibility of wavelength reuse and aggregation, thereby ensuring scalability in bandwidth assignment. For instance, heavy users (e.g., corporate users) may be assigned a single wavelength whereas light users (e.g., residential users) may share a single wavelength (Fig. 2), all on a single fiber. Based on wavelength switched scheme, in a WDM PON network, the OLT contains a multi-wavelength source used to send signals across different wavelengths. In the remote node, an optical switch (MUX/DEMUX) selects out one or more associated wavelengths and transmits them to the subscriber ONU as shown in Fig.4 in detail. We are also witnessing the exciting convergence of WDM and Ethernet, the most notable example being the National LamdaRail or NRL (www.nationallambdarail.org), which is a high-speed, experimental 40-wavelength DWDM optical testbed developed to rival the scale of research provided by the Arpanet (the Internet's precursor) in the 1960s. NLR is the first wide-area use of 10 Gbit/s switched Ethernet and is based on a routed IP network. It is owned by the university community, thanks to the plunge in dark fiber prices over the last 4 years.

2.6 Enabling Technologies of WDM PON Optical devices

One of the biggest challenges for successful DWDM PON deployment is the adoption of cost effective light source components. It is desirable to have tunable laser sources which not only support network provisioning and reconfigurability, but also minimize the production costs and backup stock numbers in the carrier's network. Several sources exist: 1) tunable VCSEL, although long wavelength (C-band) VCSEL are not yet mature up to now, it will be an ideal candidate since it has the potential for high-level system integration characteristics; 2) Spectrum-slicing using a broadband incoherent light source such as a LED may be used to realize the wavelength independent ONT. The LED can be fabricated at a low cost and modulated directly. However, its output power and modulation speed are insufficient for high speed operation; 3) a wavelength locked Fabry-Perot laser diode (F-P LD) with external spectrum spliced amplified spontaneous emission (ASE) injection was proposed recently. By injecting spectrum-sliced broadband light source (BLS) into a F-P LD, the laser is forced to operate in a quasi single mode and the mode partition noise of the F-P LD is suppressed. Although modulation index, bias current and the power of external optical excitation must be carefully chosen to maximize the efficiency, it is a promising solution to reduce cost.

Another key problem involves the survivability of the optical access network. Compared to ring networks as used in SONET/SDH, the tree-and-branch structure used in PONs is more vulnerable to single points of failures due to its topology and the lack of an alternative redundant path. If a fiber link from the RN and to the ONU is broken, the affected ONU will become unreachable from the OLT. Thus, the protection and restoration will be indispensable to provide high availability. This field is still relatively new and only few bidirectional self-healing WDM PON architectures have been proposed. These architectures utilize two different wavelength bands for the neighboring WDM PON's and cyclic property of arrayed wavelength grating (AWG).

3. Plastic optical fiber

3.1 Regular plastic optical fiber

Currently, different types of optical fiber are employed in the field. These types of fiber mainly include quartz optical fiber, glass optical fiber and plastic optical fiber. Quartz optical fiber is suitable for long distance transmission (over 1km). The quartz optical fiber has two types: single mode and multi-mode with different core area. The telecommunication fiber is usually single mode fiber due to requirment of high bandwidth, small dispersion and polarization mode dispersion. For office networks, multi-mode fiber can be employed due to low-cost. Glass optical fiber is mainly used along with POF for lighting. While for polymethylmethacrylate (PMMA) plastic optical fiber (POF), it is used for short-distance electronic appliances and cars.

POF is an optical fiber which is made out of plastic. POF typically uses PMMA (acrylic), a general-purpose resin, as the core material, and fluorinated polymers for the clad material. In large diameter fibers, the core comprises 96% of the cross section to allow the transmission of light. The core size of POF is in some cases 100 times larger than glass fiber. Although quartz fiber is widely used for infrastructures and fiber to the home, POF has been called the "consumer" optical fiber because the fiber and associated optical links, connectors, and installation are all inexpensive. In relation to the future request of high-speed home networking, there has been an increasing interest in POF as a possible option for next-generation Gigabit/s links inside the house. For telecommunications, the more difficult-to-use glass optical fiber is more common. This fiber has a core made of germania-doped silica. Although the actual cost of glass fibers are lower than plastic fiber, their installed cost is much higher due to the special handling and installation techniques required.

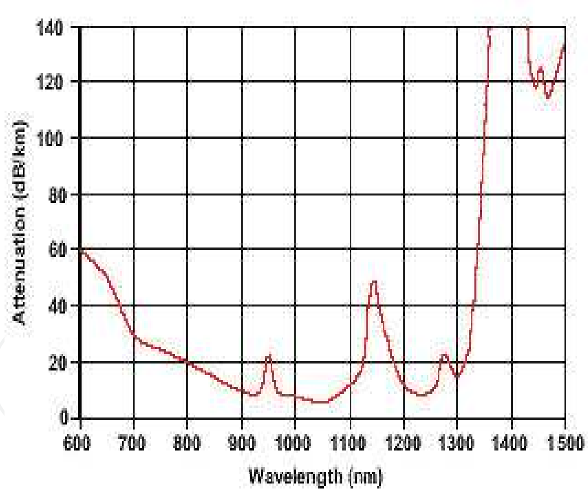


Fig. 5. GI-POF attenuation.

3.2 Graded-Index Polymer Optical Fiber (GI-POF)

Perfluorinated graded-index polymer optical fibers (GI-POFs) can provide large bandwidth and low attenuation (60dB/km) at 850–1300nm, so it is a good replacement and a low cost alternative to traditional glass. With ease of use and affordability, GI-POFs make an excellent choice for the installation of high performance fiber networks. In addition, GI-

POFs provide a higher transmission bandwidth than any other type of plastic optical fiber. Recently, a few 40Gb/s transmisison experiments have been demonstrated. Until recently, all commercially available POFs have been fabricated from non-fluorinated polymers such as PMMA and, as a result, have had a refractive index that changes in steps. Although inexpensive, these fibers are characterized by large modal dispersion and typically operate at 530nm or 650nm, which is well outside of standard communication wavelengths (850nm or 1300nm), which is where high-speed transceivers are readily available. Due to the high attenuation in the near infrared, these fibers are restricted to low performance (<100Mb/s), short range (<50m) applications in the visible region. With the advent of an amorphous perfluorinated polymer, polyperfluoro-butenylvinylether (commercially known as CYTOP®), the limitations presented by step-index POFs have been overcome. Perfluorinated fiber exhibits very low attenuation in the near infrared (~10dB/km) as shown in Fig. 5. Moreover, since the perfluorinated optical fiber can be constructed with a graded refractive index, it is capable of supporting bandwidths that are 100 times larger than those provided by conventional POFs. This is due to the interplay between high mode coupling, low material dispersion, and differential mode attenuation. Unlike conventional glass fibers, which suffer from high interconnection and receiver costs, perfluorinated GI-POFs are easy to install. To add a connector to a glass fiber, the fiber needs to be cleaved using an expensive, specialized tool. Then, epoxy is used to attach the fiber to the connector hardware. Finally, the assembled connector must be polished. In contrast, the GI-POF can be terminated using simple and inexpensive tools, connectors are crimped on, and polishing occurs in mere seconds, leading to a high quality optical link in a fraction of the time. Moreover, GI-POFs are compatible with standard multimode glass fiber transceivers. As an example, Table 2 lists the specification of the commerical GI-POF from Thorlabs.

Fiber model	50SR	62SR	120SR
Attenuation at 850nm	<60dB/km		
Attenuation at 850nm	<60dB/km		
Bandwidth at 850nm	>300MHz·km		
Numerical aperture	0.190+0.015	0.190+0.015	0.190+0.015
Macrobend loss	<0.25dB	<0.35dB	<0.60dB
Zero dispersion wavelength	1200~1650nm		
Dispersion slope	<0.06ps/nm^2·km		
Core diameter	50+5um	62.5+/-5μm	120+/-10μm
Cladding diameter	490+/-5μm		
Temperature induced atteuation at 850nm (-20 to +70^{o}C)	<5dB/km		

Table 2. specification of Thorlab's GI-POF.

Since 2006, a few world records by employing GI-POF have been achieved. The optical fiber communication conference (OFC) 2006, Georgia Tech's researchers reported that 30Gb/s on/off keying (OOK) signals are transmitted over 30m GI-POF. In ECOC 2007, Schollmann et al., reported the 40Gb/s OOK signals are delivered over 50m GI-POF with new designed multi-mode high-speed receiver. In OFC 2008, Yu in NEC Labs America reported 42.8Gb/s optical signal generated by chirped managed laser transmission over 100m GI-POF. In

ECOC 2008, Yu in NEC Labs America demonstrated 16Gb/s OFDM signal transmission over 50m GI-POF. In OFC 2009, Yang reported 40Gb/s signal transmission over 100m GI-POF based on discrete multimode modulation. By using the new spectral efficiency modulation format, such as CML and OFDM, can furthermore increase the bandwidth of the GI-POF.

4. Enabling techniques to expand the bandwidth of GI-POF

4.1 Chirped Management Laser

The demand of bandwidth for Internet traffic and access networks in the premises are rapidly increasing, fueled by video and graphic-rich applications. Therefore, the data rate at 40-Gb/s per channel is expanding to next-generation optical access networks and very-short-reach (VSR) optical links. Unlike long-haul and metro networks, access and VSR networks require low hardware cost and low operation expenses to make the transmission technology attractive and practical. Currently, there is a growing interest in utilizing directly modulated lasers (DMLs) in cost-sensitive metro and access optical links because of their potentially low cost, compact size, low power consumption, and high output power characteristics when compared with other transmitter sources using external modulation (EM) scheme such as electro-absorption modulator (EAM) or Mach-Zehnder modulator (MZM). As it is well known, however, DMLs are the carrier density modulation via drive current, giving rise to inherent and highly component-specific frequency chirp, i.e., a residual phase modulation (PM) accompanying the desired intensity modulation (IM). This chirp results in broad spectrum that severely limits the maximum transmission distance within ~20 and ~2-km SSMF for 10 and 40 Gb/s without dispersion compensation because of its interaction with fiber dispersion along the transmission link. One way to overcome this issue is to use the special fiber with a negative dispersion characteristic, which is a good choice to take advantage of the positive chirp characteristics of DMLs to increase the reach without dispersion compensation modules that can cost as much as the transmission fiber. However, it is only suitable to new deployment of optical transport system but not fit to upgrade and change of the installed base of metro fiber links.

Chirp-managed laser (CML) can provide a good optical source for access systems. In order to support high dispersion tolerance, a DFB laser biased at high direct current (DC) far above the threshold is used, digital data directly modulate this DFB laser, and a suitable optical filter is used to control the phase between the adjacent bits. The additional benefits of the higher bias are high output power, wide modulation bandwidth, low timing jitter, and suppressed transient chirp. CML technology simultaneously meets two market needs: (1) the data rate upgrade from 2.5 to 10 Gb/s, even to 40 Gb/s, in the emerging metro market, and (2) the migration of small form factor pluggable optics from short reach to high-performance long reach and WDM links. The directly modulated signals have low extinction ratio (ER) and an accompanying adiabatic chirp. An optical spectrum reshaping (OSR) filter is placed at the laser output to perform frequency modulation (FM) to amplitude modulation (AM) conversion to increase the ER and convert the slowly-varying adiabatically chirped pulses to flat-topped chirp pulses with abrupt phase transitions [9]. The output of the CML has been shown to have tolerance to both negative and positive dispersion for 10-Gb/s optical links.

The CML technique has been applied in 10-Gb/s data links with 200-km transmission over SMF without dispersion compensation and 675-km transmission using a combination of electronic dispersion compensation (EDC) and tunable dispersion compensating modules at the receiver. We have developed a 40-Gb/s CML transmitter with high dispersion tolerance using a simple combination of a directly modulated DFB laser and the subsequent conventional optical filter.

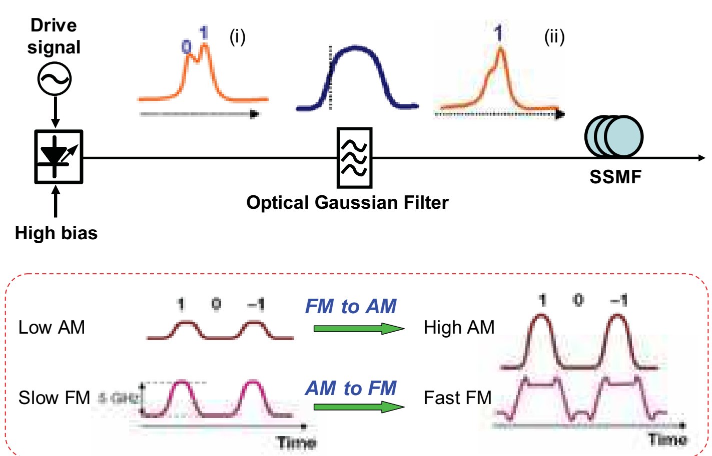


Fig. 6. Schematic of chirped-managed DML transmitter.

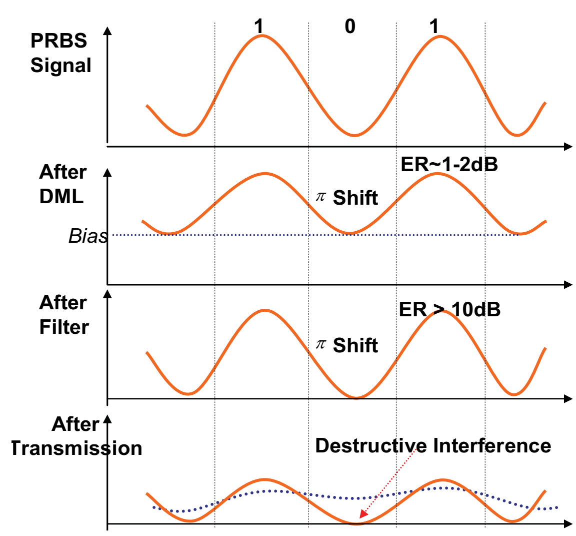


Fig. 7. Schematic of signal waveform.

4.2 The Principle of the CML Transmitter

4.2.1 Chirp Characteristics of DMLs

The performance of DMLs strongly depends on the characteristics of the laser frequency chirp. At high data rates (≥ 2.5Gbit/s), the frequency chirp of DMLs has two major components: the transient chirp and the adiabatic chirp. At lower data rates, the thermal chirp becomes dominant. Here we focus on high data rate operation. The chirp $\Delta v(t)$ of a DML is related to the laser output optical power $P(t)$ through the expression

$$\Delta v(t) = \frac{\alpha}{4\pi}\left(\frac{d}{dt}[\ln(P(t))] + \kappa P(t)\right), \tag{1}$$

Where α is the linewidth enhancement factor and κ is the adiabatic chirp coefficient. In (1), the first term is a structure-independent transient chirp, and the second term is a structure-dependent adiabatic chirp. DMLs can be classified as transient or adiabatic chirp dominated. Transient chirp dominated DMLs exhibit significantly more overshoot and ringing in output power and frequency deviations. The frequency difference between steady-state "1"s and "0"s is relatively small. On the other hand, adiabatic chirp dominated DMLs exhibit damped oscillations and large frequency difference between steady-state "1"s and "0"s. In the equation (1), the output power *P(t)* is related to the photon density *S(t)* through the relation:

$$P(t) = \frac{V\eta h v}{2\Gamma \tau_p} S(t)$$

(2)

And the photon density *S(t)* is determined by the well-known small signal single mode laser rate equations in the simple form as follows:

$$\frac{dS(t)}{dt} = \frac{\Gamma g_0 (N(t) - N_0)}{1 + \varepsilon S(t)} S(t) - \frac{S(t)}{\tau_p} + \frac{\Gamma \beta N(t)}{\tau_c}, \tag{3}$$

$$\frac{dN(t)}{dt} = \frac{I(t)}{eV} - \frac{N(t)}{\tau_c} - \frac{g_0 (N(t) - N_0)}{1 + \varepsilon S(t)} S(t), \tag{4}$$

$$\frac{d\phi}{dt} = \frac{\alpha}{2}[\Gamma g_0 (N(t) - N_0) - \frac{1}{\tau_p}], \tag{5}$$

Where *I(t)* is the current waveform injected in the active layer, *N(t)* is the carrier density, v is the optical frequency, *h* is the Plank's constant, η is the differential quantum efficiency, Γ is the confinement factor, N_0 is the carrier density at transparency, β is the fraction of spontaneous emission noise coupled into the lasing mode, g_0 is the differential gain coefficient, ε is the nonlinear gain compression factor (gain saturation coefficient), τ_p is the photon lifetime, τ_c is the carrier lifetime, *V* is the volume of the active layer and α is the same as in Eq. 1, i.e. the linewidth enhancement factor. It should be noticed that, in a first approximation, static temperature (25^{o}C) dependence of the value of each parameter has been ignored here. From Eqs. 1-5, we can see that the minimum number of parameters that have to be estimated is ten (Γ, V, N_0, β, g_0, ε, τ_p, τ_c, η, α) in addition to the lasing wavelength λ. In the (1), the α parameter can be calculated as well as the adiabatic chirp coefficient κ, which is directly related to the nonlinear gain compression factor:

$$\kappa = \frac{2\Gamma}{\eta h v V}\varepsilon\,. \tag{6}$$

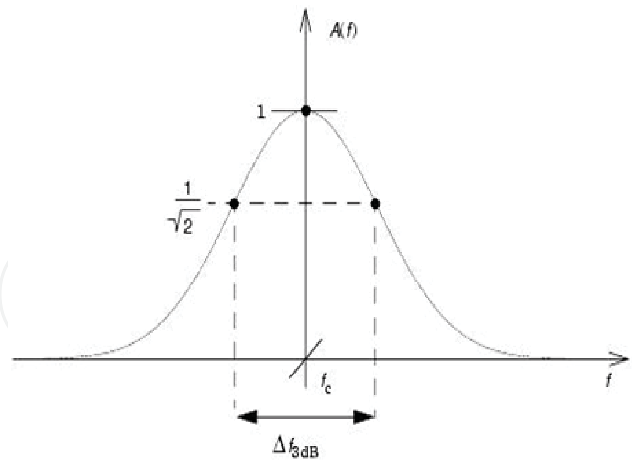


Fig. 8. Transfer function of the Gaussian filter.

Therefore, based on the Eqs. 1-6 of the chirp model (already including the drive current (DC) bias), we can design the parameters of the DMLs to offer suitable chirp response for the generation of the phase correlation.

4.2.2 Operating Principle

The high dispersion tolerance is mainly because of the phase-correlative modulation among the adjacent bits via precisely controlling the frequency chirp in the DML modulation. The adiabatic chirp makes the "1" bits blue shifted relative to the "0" bits. By controlling the modulation depth, the phase flip between 0 and π in the middle of the space bit could be realized, which leads to the destructive interference between the energies on either side of the middle of the space after the dispersion-induced broad spectrum. The π out of phase is the key to the dispersion tolerance. This resulting phase correlation and destructive interference along the fiber transmission are similar to that for optical duobinary modulation, but here, we don't require pre-coder, encoder, and external modulator in the transmitter side and the decoder in the receiver side.

The CML transmitter comprises a DML and the subsequent optical filter, the schematic diagram is shown in Fig. 6. The DML is a high-speed standard DFB laser, the optical filter is a conventional bandpass filter. The highly chirp-controlled modulation creates two distinct frequency peaks in Fig. 6 inset (i). The main function of the filter is to increase the extinction ratio by passing the "1" bits while attenuating "0" bits in inset (ii), and simultaneously suppress the transient chirp and shape it into the top-flatted chirp. To realize the proper phase flip between the bits, much higher driven bias compared to the conventional direct modulation is employed. The additional benefits of the higher bias are high output power and wide modulation bandwidth due to the high operation point. We can also achieve the stable single mode operation and low timing jitter, and make the laser be the adiabatic chirp dominated via suppression of the transient chirp because the working condition is far away from the threshold of the laser. For a 40-Gb/s data rate, the pulse width is 25 ps, to get the π phase shift, adiabatic chirp need to be equal to $\frac{\pi}{2\pi \times 25ps} = 20GHz$, that means the "1" bit has 20 GHz blue shift relative to entire "0" bit. The generation of suitable adiabatic chirp by adjusting bias and laser parameters is the first step to achieve the higher dispersion tolerance, which is due to the AM to FM conversion ("1" bit has blue shift due to the higher intensity compared to "0" bits). However, this results in a low extinction ratio (ER~1-2 dB) accompanying the higher bias. Therefore, a subsequent optical filter is employed to perform the FM to AM conversion by passing the "1" bits and attenuating the "0" bits for increasing the ER. Considering the 1 0 1 bit sequence, the original binary signal, the directly modulated signal, the filtered signal and the transmitted signal are shown in Fig. 7. The change of correlative phase flips and ER are also shown here. It is clearly seen that the eye would close and the original bit could not be recognized (the dashed line in "after transmission") without the destructive interference between the adjacent "1" bits.

4.2.3 Optimization Parameters of the Optical Filter

Since the filter plays an important part in the CML generation, we study the optimization parameters of the optical filter. The subsequent optical filter has two main functions: one is to perform the FM to AM conversion by passing the "1" bits and attenuating the "0" bits for increasing the ER. Additional effect of the optical filter is to suppress the transient chirp and shape it into the top-flatted chirp waveform for keeping the π out of phase difference during the "0" bit. In dependence on the specific application, the filter design includes development of the filter with prescribed magnitude and phase response. Various types of optical filters can be a candidate for optimal OSR filter:

1) Butterworth: Maximally flat magnitude response in the pass band, the disadvantage is some overshoot and ringing in step response.
2) Chebyshev: Better rate of attenuation beyond the pass-band than Butterworth, the disadvantage is considerably more ringing in step response than Butterworth.
3) Bessel: A uniform time delay within pass band and the best step response with minimal overshoot or ringing. The advantage is slower initial rate of attenuation beyond the pass band compared with Butterworth and other filters.
4) Rectangular and Trapezoid: Ideal selectivity, absolutely flat magnitude and phase of the frequency response. The disadvantage is that it requires truncation of the impulse response and signal delay at simulations with periodic boundary conditions.
5) Gaussian: Smooth transfer function without dispersion, more importantly, it is easily implemented to the real design and application in optical communication systems.

Based on the above mentioned reasons, we select the Gaussian filter type in our simulation model. The Gaussian filter transfer characteristic is determined by the parameter bandwidth

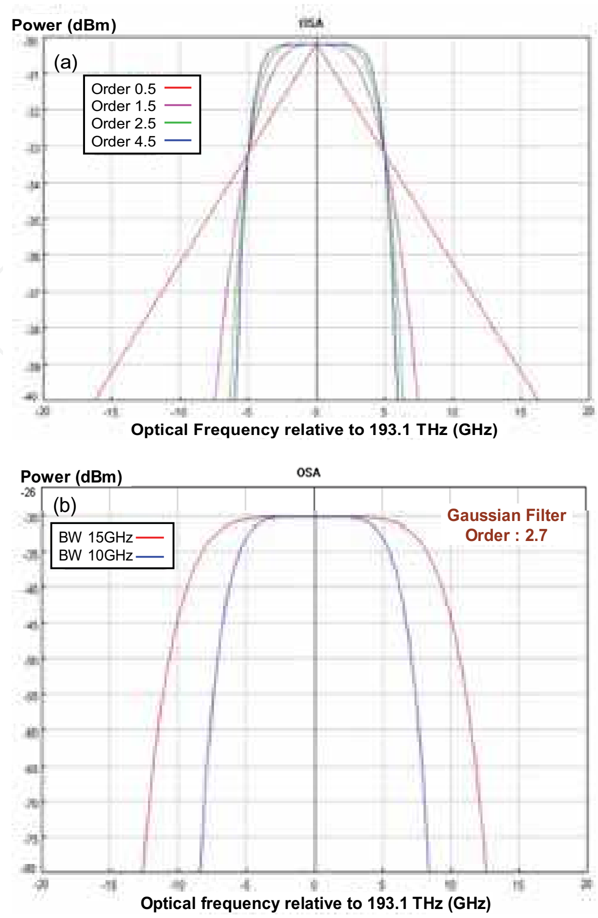


Fig. 9. Transfer characteristics of bandpass optical Gaussian filters. (a) Gaussian filter with different orders and the same 3 dB bandwidth, (b) Gaussian filter with different bandwidths and the same order.

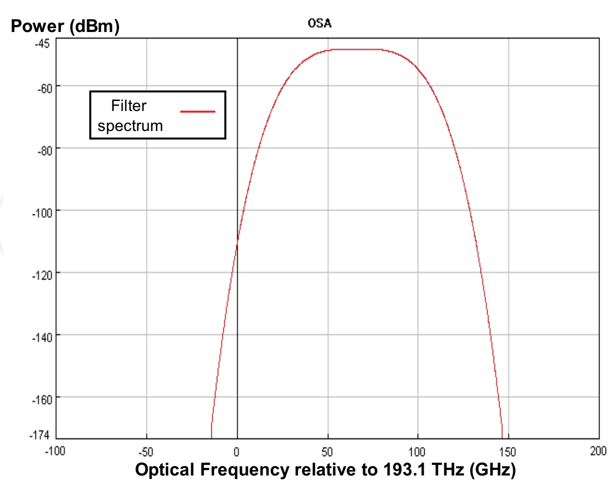


Fig. 10. Transfer spectrum for 40Gb/s signals

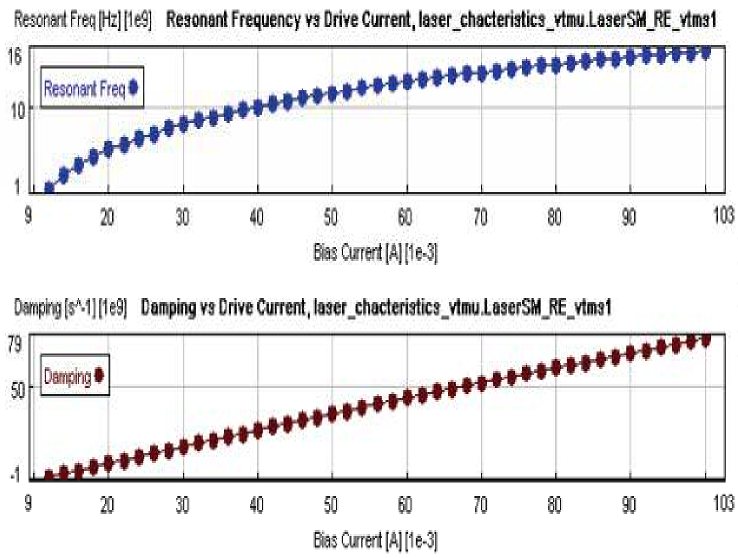


Fig. 11. Resonant frequency and damping as functions of bias current

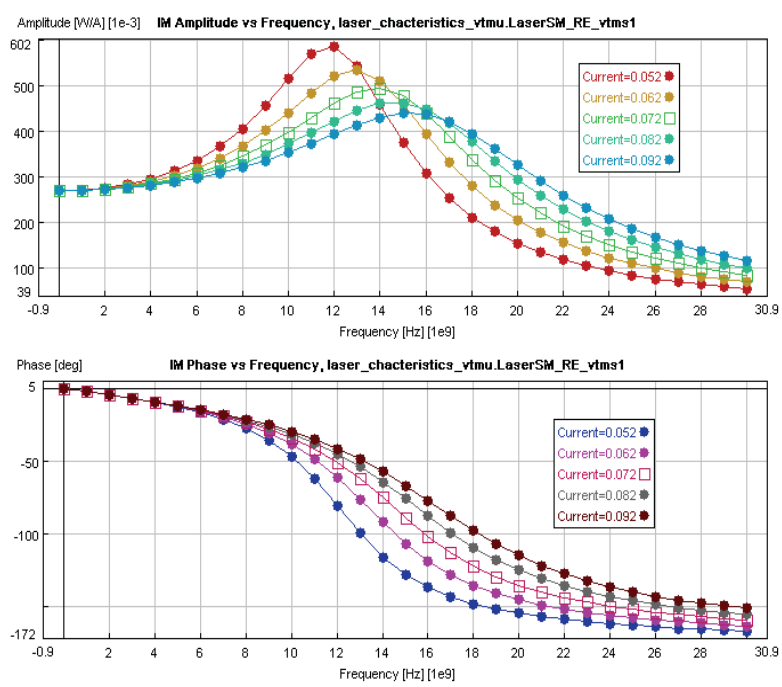


Fig. 12. Amplitude and phase response in the DML intensity modulation

(Δf_{3dB}), central frequency (f_c) and Gaussian order (n) of the filter, the expression is shown in (7):

$$T(f) = \exp\left(-\ln\sqrt{2}\left(\frac{f - f_c}{f_g}\right)^{(2n)}\right) \tag{7}$$

with the assumption of vanishing phase and $f_g = \frac{\Delta f_{3dB}}{2}$.

Filter order sets the attenuation rate at transition from pass band to stop band. Fig. 8 shows the basic transfer function of the Gaussian filter.

As mentioned before, passing the signal through the edge of the filter not only improves the ER but also produces vestigial sideband (VSB) effect, which adds blue transient chirp at the "1" to "0" and "0" to "1" transitions, further improving the eye opening after fiber dispersion. The VSB filtering reduces the information bandwidth as well. Fig. 9(a) and 9(b) shows the transfer spectrum of this Gaussian optical filter in the different of order and bandwidths set, respectively. It is noted that the Gaussian order can be set as the non-integer value. It is clearly seen that the top becomes flat and the roll- off response is very sharp. Regarding the 40-Gb/s signals, we simulate the best transfer spectrum with the bandwidth of 54 GHz and Gaussian order of 1.7. The transfer spectrum is shown in Fig. 10.

4.2.4 Parameters Optimization of DML (Laser Model)

A typical single-mode dynamic laser model (LaserSM_RE module in VPI) based on standard rate equations is used in the simulation. This module simulates the dynamics and noise characteristics of a directly-modulated single-mode laser driven by an electrical current waveform. The model describes the evolution of optical power, phase and carrier density averaged over the whole laser cavity. The model is ideal for modeling metro transmission systems using directly-modulated lasers, as it takes into account the relaxation oscillation, turn-on jitter, laser chirp, intensity and phase noise which can significantly affect the system performance. The chirp control in this directly modulated transmitter comes from two important sections: (1) Generating proper chirp frequency in the laser; (2) chirp filtering and conversion in the subsequent optical filters. We provide the theoretical analysis for the proper chirp generation (adiabatic chirp) in the laser with very high bias. According to the analysis of the chirp model, we performed the multi-parameters sweeping so as to find the optimized laser structure which is suitable to get the π out of phase for the transmission of the directly modulated signals. The results are provided below in table1:

Column Name	Units	Value
Emission Frequency	Hz	193.1e12
Reference Power	W	6.0e-3
Laser Chip Length	m	200e-6
Linear Material Gain Coefficient	m^2	9e-20
Transparency Carrier Density	$1/m^3$	1.5e24
Confinement Factor		0.3
Group Effective Index		4.0
Material Linewidth Enhancement Factor		3.5
Left Facet Reflectivity		0.3
Right Facet Reflectivity		0.3

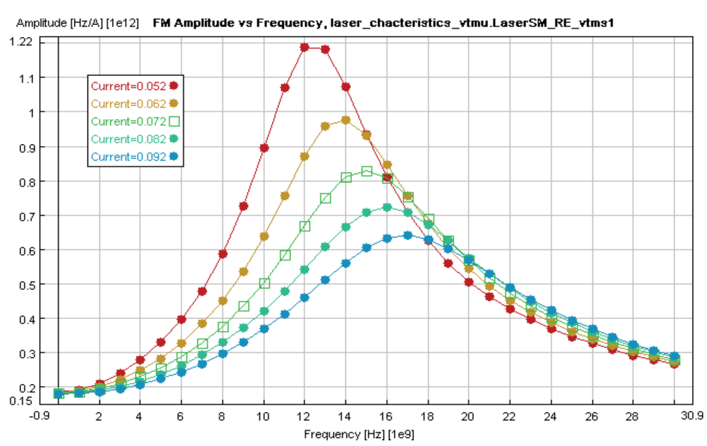
Bimolecular Recombination Coefficient	m^3/s	1.0e-16
Spontaneous Emission Factor		1.0e-4
Nonlinear Gain Coefficient		3.0e-23

Table 1. Summary of laser intrinsic parameters

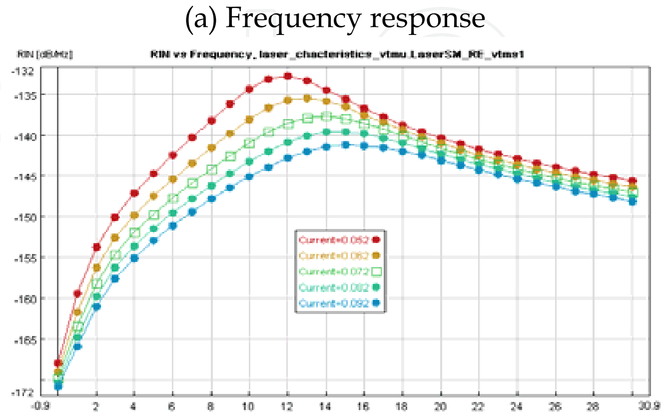
All the parameters above are used for 10-Gb/s signals, regarding 40-Gb/s signals, the drive amplitude is 21 mA and the bias is 85 mA, the nonlinear gain coefficient is changed into 5.0e-23, others keep the same as parameters for 10-Gb/s signals.

4.2.5 Bias current related characteristics

Compared with the conventional DML, the lower threshold is required because we need to bias this laser roughly 5~6 times threshold. Because of inaccuracy of the results below the threshold operation, the sweep is generated above the laser threshold for obtaining the whole working conditions. The resonant frequency and damping as a function of bias current are shown in Fig. 11. It generally increases with increasing the bias current. At the operating range of 60-80 mA bias, the slope of these two curves keeps almost stable.



(a) Frequency response



(b) RIN response

Fig. 13. Frequency modulation response and relative intensity noise spectrum.

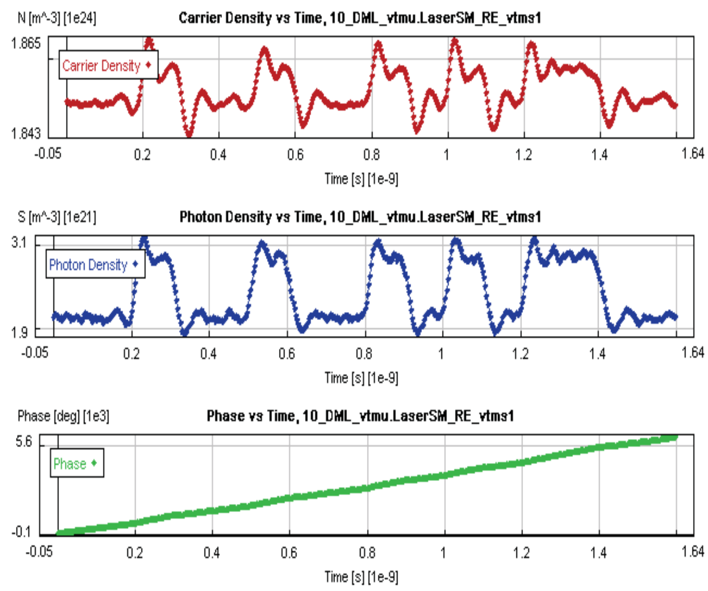


Fig. 14. Internal states as functions of time.

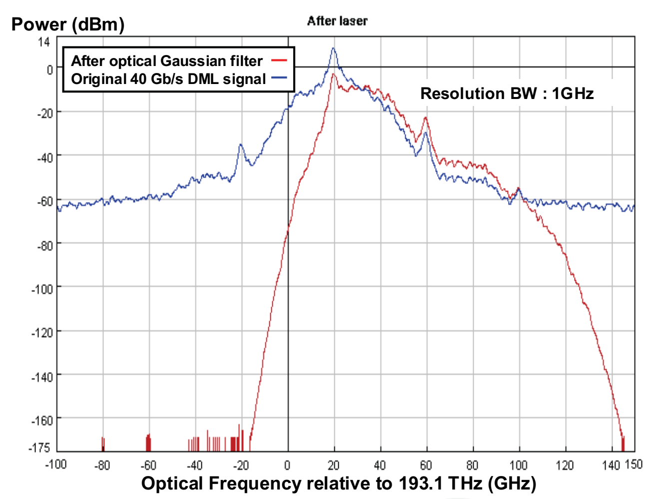


Fig. 15. 40-Gb/s signal spectra before and after optical filtering.

4.2.6 Frequency related characteristics

Figure 12 shows the small-signal intensity modulation amplitude and phase response computed at different bias currents. These response curves can be compared with measured data and used to assist in fitting the model parameter to real devices. At 14 GHz, the laser has the maximum amplitude response at the operation point of 72 mA. It is shown in Fig. 13 that the small-signal frequency modulation response and the relative intensity noise spectrum of the laser at different bias current. The frequency response increases with the optical emitted power, the 3-dB bandwidth at the bias of 72mA is larger than 10GHz and the peak of resonant frequency is 15 GHz. From the (b) in Fig. 13, the relative intensity noise (RIN) is low enough at resonant frequency of 14 GHz at the bias of 72 mA.

4.2.7 Time related characteristics

The carrier, the photon density and the phase of the optical field as a function of time are shown in Fig. 14. These results are based on the internal states of the rate equation model. We can see that the carrier and photon density have the transient change at the drop and down of the optical pulse, which is directly related to the transient chirp. And the photon density, the optical power, is the key to the conversion from amplitude modulation to frequency modulation via the adiabatic chirp. As shown in Fig. 15, the direct modulation leads to the broader spectrum compared with the external modulation scheme. Fig. 16 shows simulation results of signal waveform and chirp response at the output of this DML, after the Gaussian filter and eye diagrams after transmission. The drive amplitude to this DML is 21 mA and the bias is 85 mA. It is clearly seen that the chirp response is flat top, and the eye diagrams are wide open over 15-km SSMF transmission.

(a)

(b)

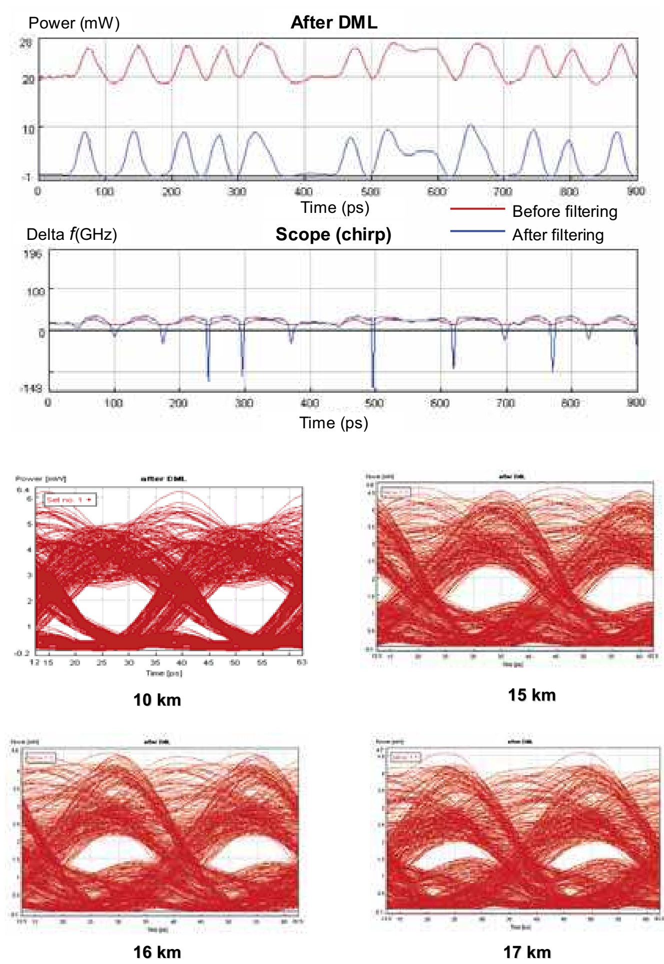


Fig. 16. (a) Waveform and flat-topped chirp and (b) eye diagrams in different distance for 40-Gb/s signals.

4.3 CML transmission performance

The experimental setup is shown in Fig. 17. A commercially available DFB laser at 1548.9 nm is directly modulated at 40-Gb/s using a PRBS with a word length of 2^7-1 or 2^{31}-1 generated from SHF 50 GHz pattern generator (SHF 12100B). The laser is biased at 94 mA and driven by 2.7 V (peak-to-peak) to produce 9 dBm average power and ~ 11 GHz of adiabatic chirp. The bias and drive voltage are optimized for the best BER performance after transmission. After the DML, a tunable optical filter (TOF) with 3-dB bandwidth of 0.32 nm and 20-dB bandwidth of 0.76 nm is used as the OSR filter to generate the desired chirp-managed signals. The optical eye diagrams before and after the filter are inserted in Fig. 18. The extinction ratio of the DML output before the OSR filter is 1.3 dB and increased to 5 dB, after the OSR filter. The optical spectra before and after the OSR filter are shown in Fig. 19. After the OSR filter, the CML signal is launched into different lengths of standard SMF-28 fiber. The dispersion and loss at

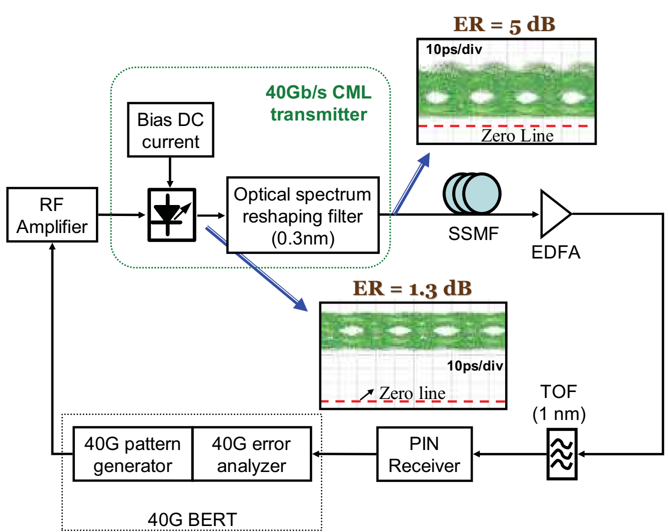


Fig. 17. Chirp-managed 40-Gb/s transmission experimental setup. (TOF: tunable optical filter.)

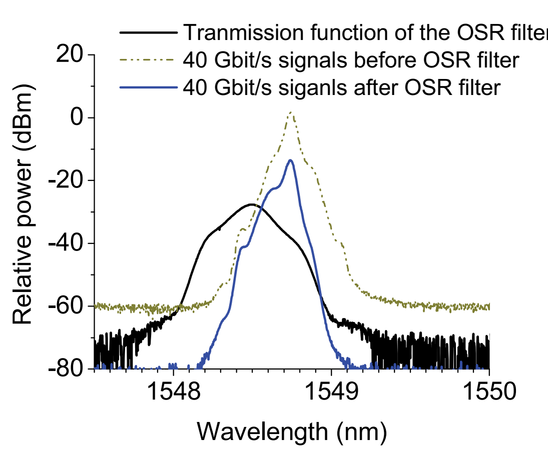


Fig. 18. Received optical spectra with 0.01-nm resolution before and after OSR filter.

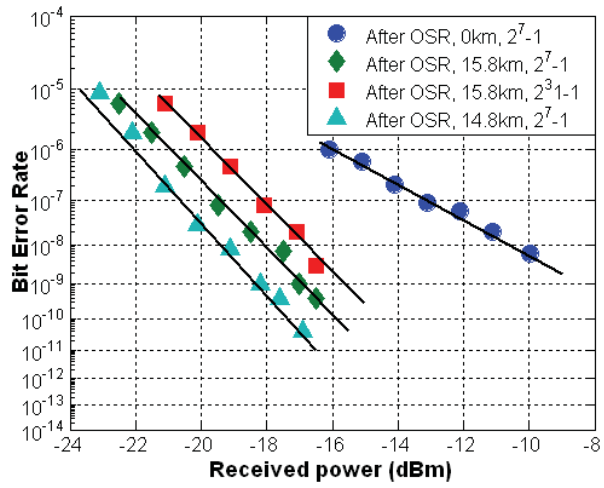


Fig. 19. Measured BER curves of 40-Gb/s CML signals in different distance and PRBS length.

1548.9 nm of this fiber are 17 ps/nm/km and 0.2 dB/km, respectively. The receiver consists of an EDFA pre-amplifier and a 50 GHz PIN photodiode. Another TOF with 3-dB bandwidth of 1.4 nm is used to reduce amplified spontaneous emission (ASE) noise from the EDFA. A SHF 50 GHz error analyzer (SHF11100A) is used to measure the BER performance. The clock signals for the SHF error analyzer are directly obtained from the pattern generator. Fig. 19 shows the BER performance for the 40-Gb/s CML signals transmission over different fiber lengths with different patterns. When the PRBS pattern is 2^7-1, the receive sensitivity at a BER of 10^{-9} after transmission over 14.8 km and 15.8 km are -17.6 and -16.5 dBm, respectively. Increasing the pattern length to 2^{31}-1, the BER increases to 10^{-8} after transmission over 15.8 km at -16.5 dBm received power. The pattern dependence penalty is mainly due to the low frequency thermal chirp of the DFB, which is not compensated in this experiment.

4.4 Transmission over Graded-Index Plastic Optical Fiber

In the above section, we have reported the application of the chirp-managed transmitter operating at 42.8-Gb/s data rate over standard SMF without dispersion compensation. In this section, we demonstrate that GI-POF can transmit 40Gb/s signal with a BER smaller than 2×10^{-3}.

The experimental configuration is shown schematically in Fig. 20. The CML transmitter setup, including the driving voltage of the laser, and the OSR filter is kept similar as these in Fig. 16. The optical spectra with 0.01-nm resolution before and after OSR filter are shown in Fig. 20 insets (a) and (b). After the OSR filter and EDFA, the CML signal is launched into 100-m commercially available GI-POF (GigaPOF-50SR, Thorlabs) for transmission.

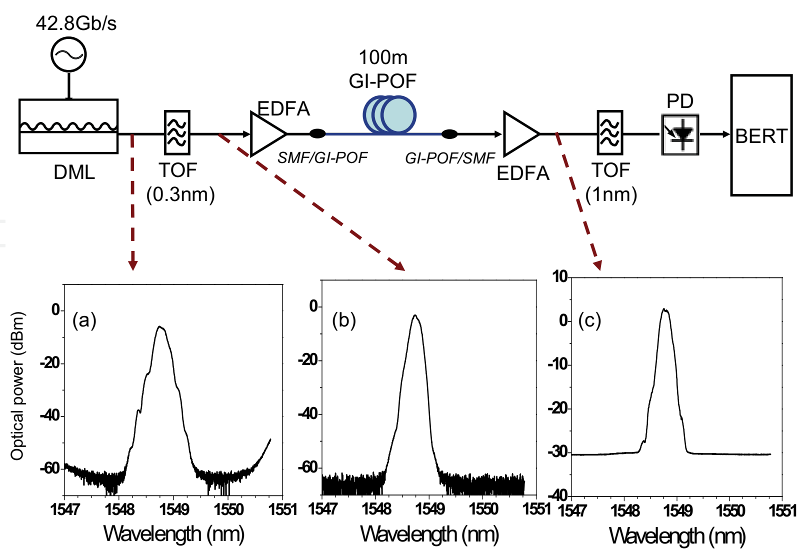


Fig. 20. Schematic of experimental setup for the chirp-managed signal transmission over 100 m GI-POF at 42.8 Gb/s. Inset: received optical spectrum (0.01 nm). (a): Before OSR filter; (b): After OSR filter; (c): After 100m GI-POF.

Due to the lack of a photodiode with multi-mode input and a bandwidth up to 40 GHz, we use a regular photodiode with single-mode input and bandwidth of 45 GHz. Therefore, there is additional insertion loss when we connect the GI-POF with the SMF-28. The coupler loss from GI-POF to SMF-28 is approximately 10 dB. The signal power launched into GI-POF is 23 dBm, and the output power after the 100-m GI-POF is -4 dBm. The insertion loss is over 27 dB, however, the insertion loss at this wavelength can be largely reduced when the laser is operated at 1310 nm or 850 nm. After coupling with the SMF-28, the optical power is -14 dBm. The receiver consists of an EDFA preamplifier and a 45 GHz high-speed single-mode coupled photodiode. The received optical spectrum after preamplifier is shown in Fig. 20 inset (c). Another TOF with 3-dB bandwidth of 1 nm is used to reduce ASE noise from the EDFA. A commercial error analyzer is used to measure BER performance while the clock signals for the error analyzer are directly obtained from the pattern generator. We evaluate the optical signal-to-noise ratio (OSNR) requirement for this CML laser at 42.8-Gb/s as shown in Fig. 20. The measurement results show that the required OSNR for the 42.8-Gb/s CML signal is 24.8 dB (0.1 nm) when the BER equals to 2×10^{-3}.

Fig. 21 shows the measured BER performance and the corresponding eye diagrams after 100-m GI-POF transmission at different bit rates, including 34, 36, 40 and 42.8 Gb/s. For the CML signal before transmission, the lowest BERs are 3×10^{-6} and 1×10^{-7} at the bit rate of 42.8 and 40-Gb/s, respectively. After transmission over 100-m GI-POF, the BER value is raised from 1.0×10^{-9} to 3.6×10^{-4} while the bit rate increased from 34 Gb/s to 42.8 Gb/s. Even if the bit rate is 42.8 Gb/s, error-free transmission can be realized at the BER of 3.6×10^{-4} using FEC modules.

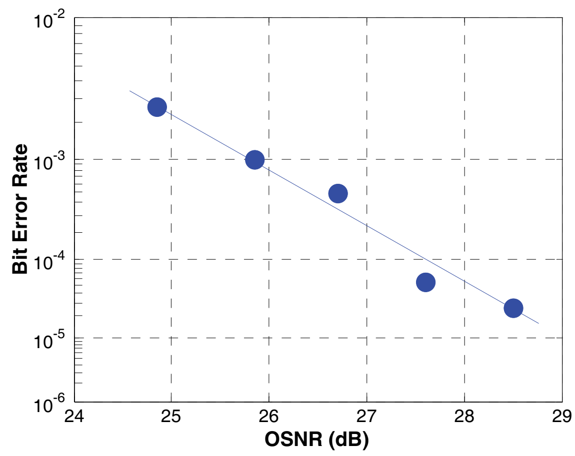


Fig. 21. Measured BER as a function of OSNR for the CML signal at 42.8 Gb/s before transmission.

4.5 OFDM technique and application in POF system

4.5.1 OFDM technique

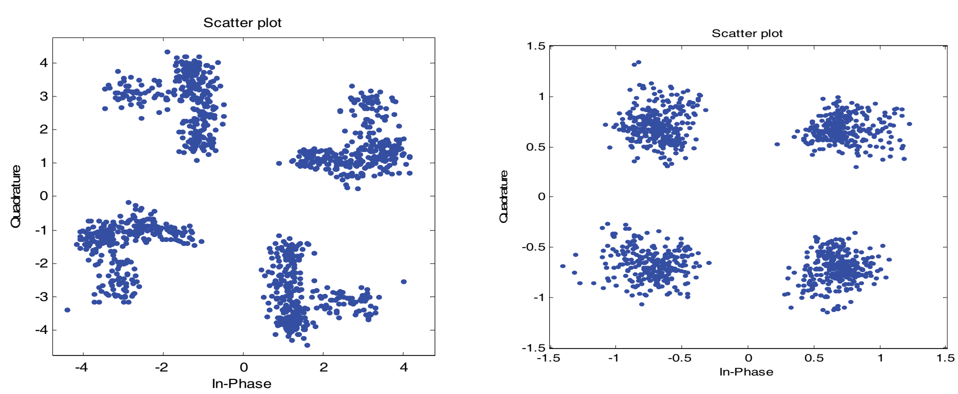
Orthogonal frequency division multiplexing (OFDM) is a particular frequency-division multiplexing (FDM) scheme utilized a digital multi-carrier modulation method. Every portion of input data is transmitted on one of the available closely-spaced orthogonal subcarriers. OFDM is divided into several parallel data up and down streams or channels. Sub-carriers are modulated with conventional digital modulation schemes (such as Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK)) at a low symbol rate, which can maintain total data rates similar to conventional single-carrier modulation schemes at the same bandwidth.

The primary advantage of OFDM over single-carrier schemes is its ability to conquer severe channel conditions, especially the Multi-Path Effect. Channel equalization is simplified because it could be viewed as using a lot of slowly modulated narrowband signals rather than one rapidly modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, which makes it possible to handle time-spreading and eliminates inter-symbol interference (ISI). This mechanism also facilitates the design of single-carrier networks, where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple transmitters could be combined constructively, rather than interfering that would typically occur in a traditional single-carrier system.

The first OFDM experiments were presented is 1960s' military radio link. At that time, actual civil use of OFDM was limited and the practicability of the concept was questioned. When the digital communication and integrated circuit chip have been tremendously promoted, OFDM are developed as a popular scheme for broadband digital communication, whether wireless or over copper wires, adopted in applications such as digital television and audio broadcasting. Over the last decade, OFDM is exploited for wireless communication system, and also becoming a basic technique for next generation broadband wireless access network. Today it is proved in practice that traditional wireless communication systems, like TDMA, FDMA or even CDMA are not capable of meeting the required criteria because of their inherent limitations. This is the reason why a large amount of research effort in radio communications is focused on multicarrier transmission methods, and these techniques are now considered the only way to support future demands. OFDM/OFDMA is the criteria technique of Long Term Evolution (LTE) which is the extension of 3GPP (3rd Generation Partnership Project).

In recent years, seamless integrated wired and wireless access technology is becoming an interesting research subject. A significant solution of this subject is OFDM radio frequency signal transmission over fiber. Radio-Over-Fiber (ROF) has well known scheme for distributing RF and microwave signals, such as low transmission loss and wide bandwidth. OFDM is more and more attractive in optical communication application, which appears in a large number of optical researches, such as long-haul transmission and WDM-PON. The combination of OFDM and ROF is increasing the high-speed wireless data transmission and video distribution in future broadband access network.

People are paying more attention to do channel optimization in optical domain, such as dispersion shift fiber or dispersion compensating fiber. However, electrical optimization is more effective to make received OFDM-ROF signal better. For instance, pilots that are padded into OFDM symbol can equalize noises and phase distortions of received signal. OFDM-QPSK baseband signal transmitted over 50 km SSMF by 60-GHz ROF technique is used to prove the effect of electrical equalization. The received QPSK constellations without and with equalization are shown in Fig.22 (a) and (b). In this demonstration, 60 of 64 sub-carriers are used to transmit data with QPSK modulation; pilots are carried by the other 4 sub-carriers. Coarse channel estimation is achieved from received pilots. Fig.22 (a) depicts QPSK constellation with severe noises and phase distortion caused by dispersion and nonlinear effect. Great impact of electrical equalization which compensates signal's distortions is shown in Fig. 22 (b).



(a) (b)

Fig. 22. QPSK constellations without (a) and with (b) equalization.

4.5.2 Optical OFDM Signals over GI-POF

In this section we will experimentally demonstrate the transmission of upconverted 16Gbit/s OFDM signals on 24GHz microwave carrier over 50m GI-POF at 1310nm.

The experimental setup of the proposed OFDM signals transmission over GI-POF is shown in Fig. 23. The lightwave from the DFB laser-diode (LD) at 1310nm with the output power around 10dBm is modulated by an intensity modulator (IM) driven by up-converted OFDM signals. The 16Gbit/s OFDM signals are generated by OFDM transmitter and then up-converted to 24GHz to realize RF-OFDM signals via an electrical mixer. The up-converted spectrum is inserted in Fig. 21. We can see that the bandwidth of the OFDM signal is 8GHz. The OFDM baseband signal is generated offline and uploaded into a Tektronix AWG7102. The waveforms produced by the arbitrary wave generator (AWG) are continuously output at a sample rate of 20GHz (8bits DAC, 4GHz bandwidth). The FFT size is 256, from which 200 channels are used for data transmission, 55 channels at high frequencies are set to zero for over-sampling, and one channel in the middle of the OFDM spectrum is set to zero for DC in baseband. 10 training sequences are applied for each 150 OFDM-symbol frame in order to enable phase noise compensation. At the output of the AWG, the low-pass filter (LPF) with 5GHz bandwidth is used to remove the high-spectral components. Subsequently, the RF-pilot tone is created by inserting a small DC offset before an analogue I/Q mixer is used to up-convert the OFDM signal from the baseband to an 8.5GHz intermediate frequency (IF). The electrical spectrum of the original signal is shown in Fig. 24(a)

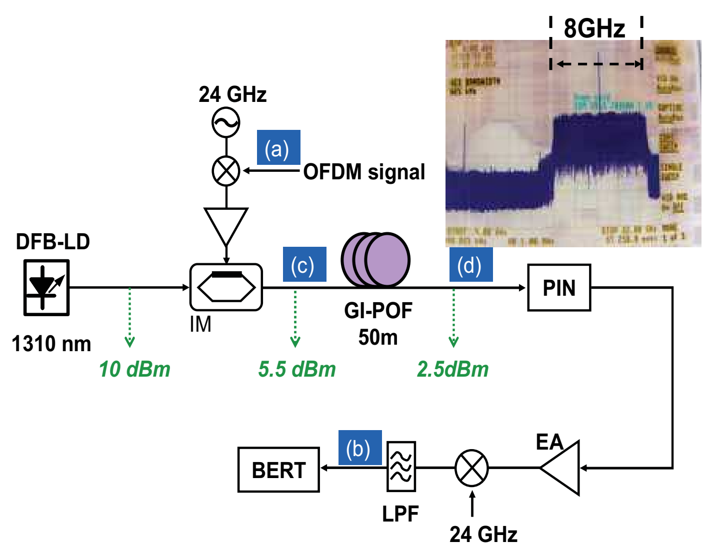


Fig. 23. Experimental configuration for 16Gb/s OFDM transmission over GI-POF. EA: electrical amplifier; IM: intensity modulator; GI-POF: graded-index plastic optical fiber; PIN: receiver; LPF: low pass filter. Inset: electrical spectrum of the OFDM signal after up-conversion.

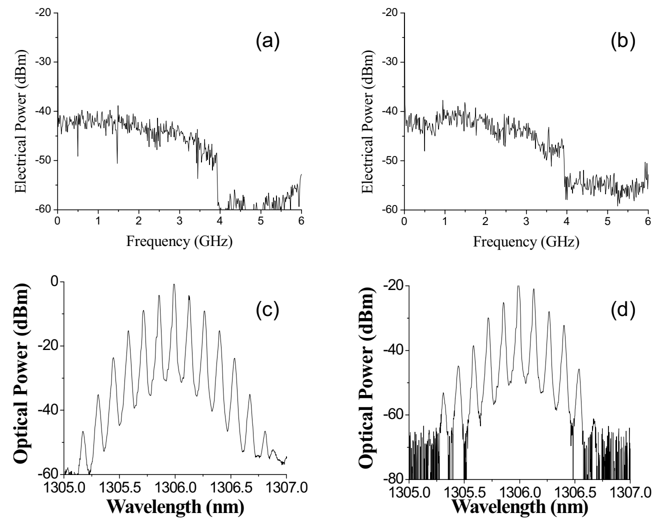


Fig. 24. Received electrical spectra: (a) after arbitrary waveform generator, (b) after LPF; received optical spectra with 0.01nm resolution: (c) before, and (d) after GI-POF at the point (a)-(d) in Fig. 1, respectively.

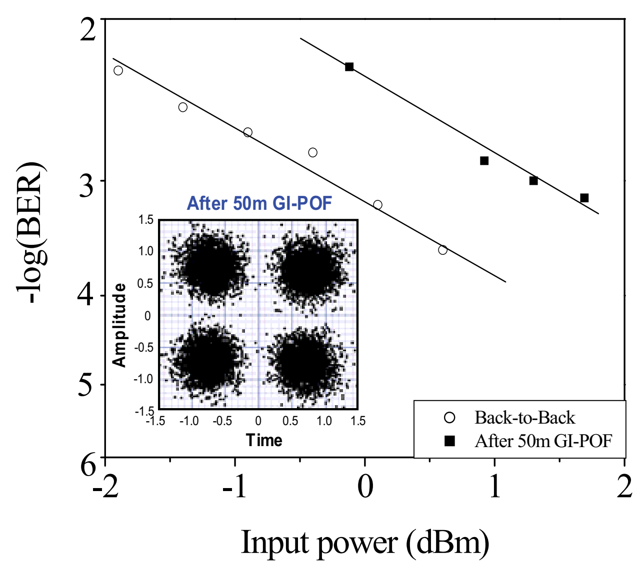


Fig. 25. Measured BER curves and the constellation figure of back-to-back and after 50m GI-POF.

that was measured at the point (a) in Fig. 23. The IM is driven by the OFDM signals to create double sideband (DSB) optical signals. The bias and the power of the RF signals are carefully adjusted to obtain proper power ratio between the optical carrier and the first-order sideband signals. The optical spectrum with 0.01nm resolution after the intensity modulator is shown in Fig. 24(c). After IM, the signal was launched into 50m of commercially available GI-POF for transmission. The core of the GI-POF is 50 μm with 60dB/km attenuation at 1300 nm. The signal power launched and output of GI-POF was 5.5 and 2.5dBm. The optical spectrum after transmission is presented in Fig. 24(d). A PIN receiver is used in the receiver side with the bandwidth of 29GHz and a 50μm multimode-coupled input. Before low pass filter (LPF), a 24GHz electrical LO signal is mixed to down-convert the electrical signal to its baseband form. The down-converted signals are sampled with a real-time oscilloscope (Tektronix 6154C) and processed off-line. The electrical spectrum of down-converted signals is shown in Fig. 24(b). The measured BER of back-to-back and after transmission is shown in Fig. 25 and the constellation figure after 50m GI-POF is inserted. One million bits have been evaluated for all values of BER reported in this work. We can see that there exists signal degradation after 50m GI-POF. But the BER is still lower than $1x10^{-3}$, which is below the limitation of forward error correction (FEC) at $2x10^{-3}$. The main reason is the degradation of optical signal-to-noise- ratio (OSNR) from the fiber with an insertion loss of 3dB and modal dispersion.

5. Conclusions

We have reviewed broadband optical access networks to provide the needed bandwidth and flexible connectivity for future Internet users. For transmission fiber in broadband optical access network, GI-POF can be used to provide up to 40Gb/s huge bandwidth and low insertion loss by some special design. New modulation format signals can further extend the transmission distance of the signal in the GI-POF. Directly modulated laser with special optical filtering technique can generate a laser to increase the dispersion tolerance, and further more increase the bandwidth of the GI-POF. We have demonstrated that this 40Gb/s CML signals can be tranmitted in GI-POF over 100m distance with BER smaller than FEC limitation. We have proposed and experimentally demonstrated a transmission system with ultra-bandwidth up to 16Gbit/s OFDM signals over 50m GI-POF. The experimental results illustrate that the transmission over GI-POF degrades the optical signal performance due to the reduction of OSNR in the fiber link. However, this system still can realize error-free transmission when the FEC is used.

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The optical fibre technology is one of the hop topics developed in the beginning of the 21th century and could substantially benefit applications dealing with lighting, sensing and communication systems. Many improvements have been made in the past years to reduce the fibre attenuation and to improve the fibre performance. Nowadays, new applications have been developed over the scientific community and this book fits this paradigm. It summarizes the current status of know-how in optical fibre applications and represents a further source of information dealing with two main topics: the development of fibre optics sensors, and the application of optical fibre for telecommunication systems.

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