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Chip-Scale Programmable Photonic Filters

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1. Introduction

The integrated circuit has driven the electronics industry for half a century of continuous advancement because of three key attributes: an integrated manufacturing platform, a scalable architecture and programmable response. The first attribute, an integrated manufacturing base, provides a cost advantage that stems from a common core of materials science and allows a predictive roadmap for fabrication tool and process advances. The semiconductor manufacturing platform also grants significant reliability and survivability benefits. Secondly, the architecture of integrated electronics has been fundamentally scalable with clear figures of merit – feature size, transistor number per die, clock speed, etc – to demarcate the frontier. The key to this scalability is the ability to regenerate a signal, and historically this stems from the presence of gain in the electronics. Systems with gain are often classified as active, and it is important to note that no sophisticated system or large scale network has evolved that is passive. Finally, programmability provides a third economy, that of manufacturing scale. Because of the power to program microprocessors, DSPs and FPGAs, the development and manufacturing costs of these devices can be amortized over a large number of "niche" applications with medium or small market sizes. The profitable "market of one" is achieved routinely by programmed microprocessors, digital signal processors (DSPs) and field programmable gate arrays (FPGAs). Since the same integrated circuit design may be used in a tremendous number of applications, the fixed costs of design, development and wafer fab can be amortized across disparate small markets. Further, it is quite common to re-program any of these integrated circuits remotely to improve or adapt to their mission.

By contrast, there is the photonics industry, which is today reminiscent of the electronics industry in the 1960s. As an industry, photonics and optics is a heavily fragmented array of customized markets each worth only a few million dollars per year in revenues. We believe that one reason for this is the general philosophy of photonics which concentrates at the component level. In most development work a photonics device is carefully optimized for a specific application, and strategies for multiple markets and design re-use seem to be kept as secondary concerns. Consequently, a photonics module or system is characterized as an assembly of discrete components with very low levels of integration, manufactured with a high manual labor content. These parts are comprised of very different materials that are often epoxied together with glue applied by hand with the tip of an optical fiber. Today, there are few true photonic integrated circuits. Most optical systems are passive. At best, particular components are tunable or adjustable, but not programmable.

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However, recent work has shown that the three main lessons of the integrated circuit can be brought to photonics (MacFarlane 2003, MacFarlane & Dowling 2004, Coleman et al 1997). In doing so, an extremely powerful information processor can be developed that will continue to drive improvements in overall processing power in the post CMOS era. The photonic integrated circuit described herein is a versatile, programmable, scalable architecture that will process photonic signals, and provide a sophisticated and practical interface with existing electronics. In particular, two key advances may be leveraged to this end. The first is the use of nanotechnology to provide on chip coupling and routing from one component to another. In the research described here this nanotechnology is integrated in a seamless manner onto the wafer. Second, recent advances in the state of practical technology of photonic devices, components and systems have provided us with the basic tools to design and build photonic filters that are not merely passive but active. This development of the active optical filter is an advance that is analogous to bringing a transistor to an electric circuit comprised of inductors, capacitors and resistors, and promises to provide the same revolutionary impact to photonics. An active filter has power gain as an integral part of its operation. Active filters, with gain, perform better than passive filters because their quality factor, a fundamental figure of merit, is higher. Functionally, active filters with high quality factors can sort or discriminate favoured frequencies with much higher precision than passive filters with low quality factors. A passive filter may only sort, or discriminate, one frequency from other frequencies by attenuating unwanted frequencies. An active filter can use its gain to accentuate, or amplify the desired frequencies in addition to attenuating the unwanted frequencies.

2. Nanophotonic couplers

A wide range of exciting results have emerged in the past several years in the area of nanophotonics (Zachidov et al 1998, Roh st al 2000, Osterback st al 2000, Yeoh et al 2001, Notomi 2002). The nanoscale engineering of optical materials and structures have provided revolutionary precision for traditional tasks and promise significantly new functionality. I see the field of nanotechnology as a key enabler for integrated photonics, and in particular integrated photonics with active elements, or gain. In the simplest application nanophotonic couplers can be used to route or direct optical signals from one component to another, or to several others. These couplers can also be used to multiplex or demultiplex different wavelength lasers on a single chip, direct optical signals to an embedded modulator or detector, and provide input-output coupling onto and off of the chip. The couplers may be

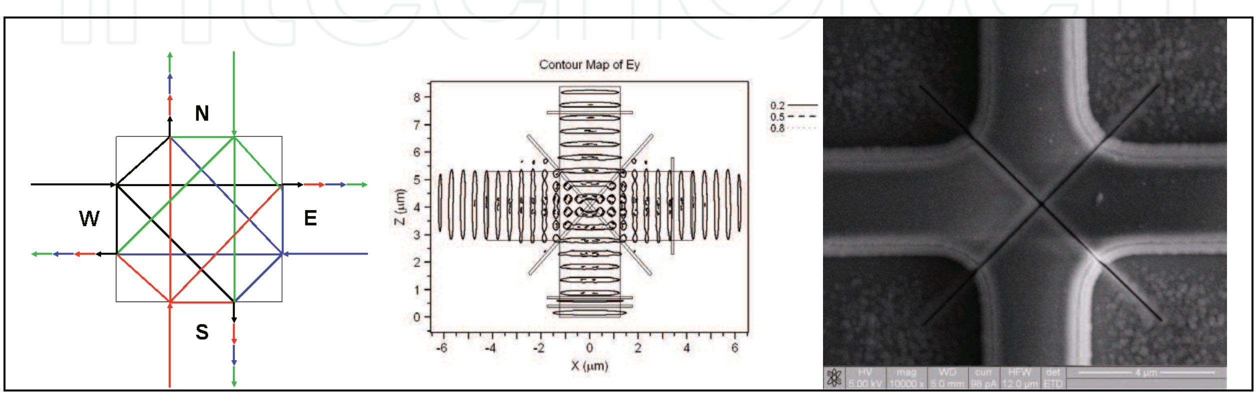

Fig. 1. 4-port nanophotonic coupler concepts

spectrally flat or can provide filter functions including wavelength selectivity and dispersion (chirp) control.

Of particular interest here is the four port nanophotonic coupler shown in Fig. 1. The four port coupler has 4 inputs and four outputs and hence can mix information from four adjacent filter stages. Realization of the four port couple may be accomplished through crossed grating structures or through deep trenches that are etched into the substrate to provide for frustrated total internal reflection.

3. Architecture

The particular class of devices described herein is optical filters. Passive optical filters comprise a market size of approximately $1Bn covering a variety of high tech and commodity applications. Technically passive filters include thin film filters, Fabry Perot etalons, fiber ring resonators, fiber Bragg gratings, interleavers, array waveguides, and star couplers. Applications for many of the more advanced architectures lie in the optical telecommunications arena, however thin film "lattice" structures also find application in antireflection coatings (lenses) and color measurement, lighting and displays. A surprising number of these applications demand precision manufacturing techniques. Producing precision devices with fixed responses for a large variety of applications across many niche markets is an economic and practical challenge. A manufacturer of precision filters for diode laser stabilization recently tripled lead times to 6 weeks to account for expected coating run delays. Such anecdotes are not, unfortunately, uncommon.

The measure of a filter's performance is the quality factor, $Q=\omega/\Delta\omega$. For a bandpass filter, the quality factor may be interpreted as the precision with which one frequency may be separated or distinguished from another. The Q would be the ratio of a frequency divided by an uncertainty in frequency. In general, a filter with a high quality factor is better than one with a low quality factor. A passive filter may only sort, or discriminate one frequency from other frequencies by attenuating or re-directing the unwanted frequencies. An active filter can use its gain to accentuate, or amplify the wanted frequencies in addition to attenuating the unwanted frequencies. This is a physical interpretation for why active filters yield higher Q's, for higher performance.

Schematically the difference between a passive optical filter and an active optical filter can be seen in Fig. 2. Figure 2 shows the signal flow for one stage of an optical lattice filter, a class of filters that includes Fabry Perot etalons and thin film filters. Shown are two mirrors or interfaces labeled k-1 and k, respectively with transmission coefficients and reflection coefficients. The space between the mirrors or the material thickness gives rise to a delay block, labeled $z^{-1/2}$, to invoke the z-transform. Most lattice filters are multistage structures. For example, a modern thin film interference filter may have more than 100 stages. The mathematical treatment of these devices entails unraveling these structures stage by stage, and this process is often called layer-peeling. For this layer peeling, the z-transform technique is a particularly useful design technique that has been pioneered by the author and is now used extensively in engineering practice (MacFarlane and Dowling 1994, Dowling and MacFarlane 1994, Narayan et al 1994, Narayan et al 1995). The same structure is shown in Fig. 2, including a gain block, G. Many of the same design techniques developed for the passive lattice filter may be applied to the active filter.

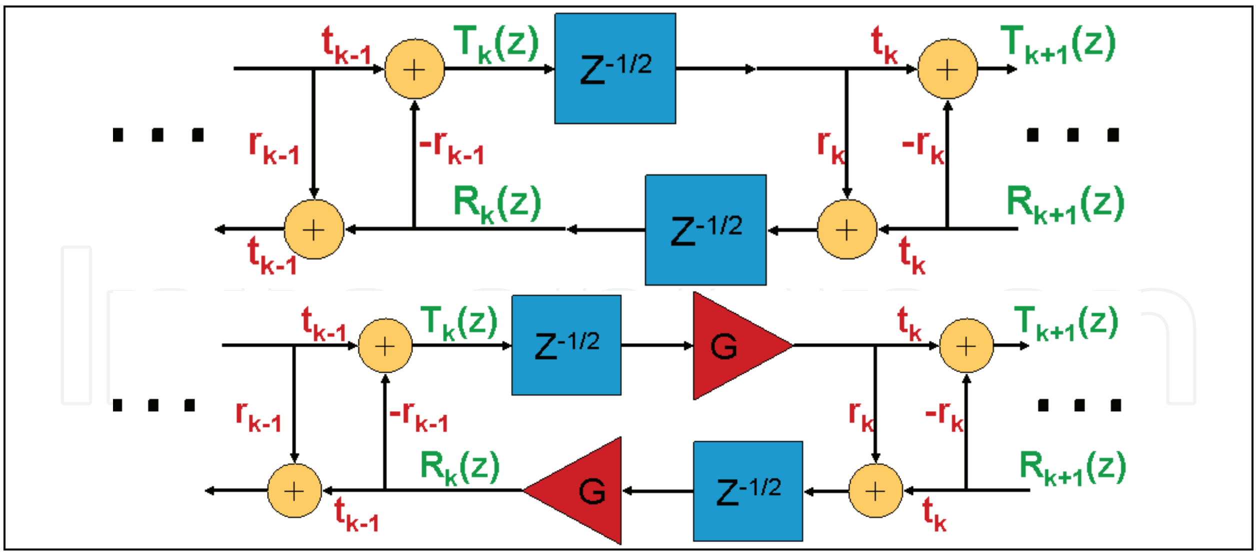

Fig. 2. Lattice filter stages comparing a passive and active filters

In a traditional lattice filter, the flow of signals is forward and backward in one dimension. At the interfaces between stages, or layers, these forward and backward signals combine, with different relevant phases for different frequency components. This delay and superposition action provides for a very rich Infinite Impulse Response (IIR) filter. The lattice structure is closely tied to linear prediction and joint process estimation (Haykin 2002, Proakis and Manolakis 1996), and is generally appreciated in signal processing because it offers desirable stability and robust round-off properties (Haykin 2002, Proakis and Manolakis 1996). However, the surface grating structure provides for significantly more versatile filter architecture. A unique two dimensional flow of signals may be realized if four-port couplers are used.

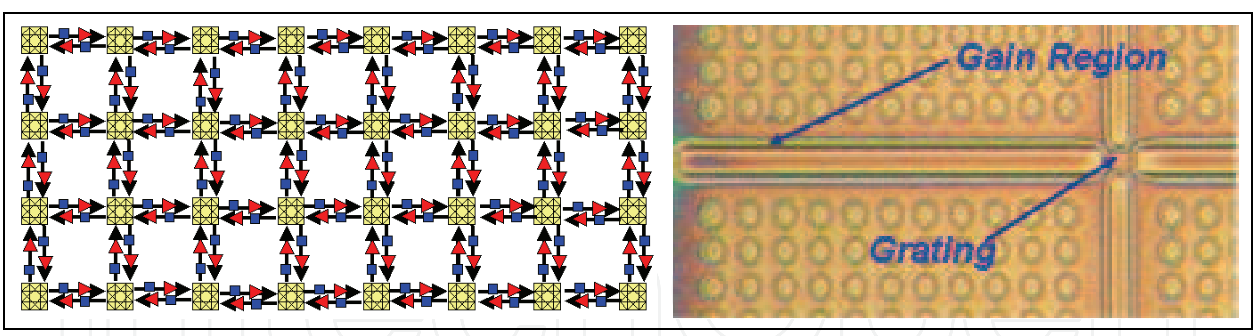

Fig. 3. Two dimensional active lattice filters.

There are significant technical and economic advantages to this two dimensional active lattice filter. Note that the two dimensional architecture optimally uses the two dimensional chip real estate. Operationally, the two dimensional active lattice filter is fully tunable, and allows multiple inputs and outputs. The tunability allows adjustment of the filter response, but also a more basic selection of the type of filter implementation. The device allows for an optimal filter realization for an application. Thus in working with the physical device, an engineer may optimize a design not only with respect to the order of the filter but also with respect to the form, or structure, of the filter. Importantly, completely new filter responses can be programmed on the same device in approximately one nanosecond. The combination of programmability and ease of manufacture provides the optical equivalent of a Field

Programmable Gate Array (FPGA). FPGA economics are extremely attractive because a standardized device can be leveraged across a host of custom, even niche, applications. The fixed costs of development and manufacturing plant can be amortized across a large number of markets, providing economies of scale that are currently unique in the photonics world.

4. Analysis

One strategy for the analysis and design of two dimensional lattice filters follows by extending the 2x2 matrix method for traditional lattices to higher order. In a traditional lattice structure one typically considers a forward propagating signal and a backwards propagating signal which together comprise a vector of rank 2 at any given stage. Movement from stage to stage is governed by a 2x2 scattering matrix. For N stages of a traditional lattice, a total 2x2 matrix may be written as the product of N 2x2 layer matrices. In the thick lattice filter, the 2x2 matrices still hold, albeit their arguments are significantly more complicated. For an MxN two dimensional lattice structure introduced here, one should consider M forward propagating signals and M backward propagating signals which together comprise a vector of rank 2M at any given stage. Movement from stage to stage is then governed by a 2Mx2M scattering matrix, and a total system matrix or rank 2Mx2M may be written as the product of N 2Mx2M layer matrices. However, most layer peeling applications (MacFarlane & Dowling 1994, Dowling & MacFarlane 1994, Narayan et al 1994, Narayan et al 1995, Haykin 2002, Proakis & Manolakis 1996) for analysis and design rely upon the 6x6 scattering matrix that describes the movement from stage k to stage k+1. The conversion of the transfer matrix to the scattering matrix follows by recognizing the 2Mx2M transfer matrix as 4 MxM sub matrices:

$$\begin{bmatrix} \vec{\mathbf{F}}_{\mathbf{k}} \\ \vec{\mathbf{B}}_{\mathbf{k-1}} \end{bmatrix} = \begin{bmatrix} \mathbf{\Psi}_{\mathbf{FF}} & \mathbf{\Psi}_{\mathbf{FB}} \\ \mathbf{\Psi}_{\mathbf{BF}} & \mathbf{\Psi}_{\mathbf{BB}} \end{bmatrix} \begin{bmatrix} \vec{\mathbf{F}}_{\mathbf{k-1}} \\ \vec{\mathbf{B}}_{\mathbf{k}} \end{bmatrix} \tag{1}$$

Two matrix equations may now be written:

$$\vec{\mathbf{F}}_{\mathbf{k}} = \mathbf{\Psi}_{\mathbf{FF}} \vec{\mathbf{F}}_{\mathbf{k-1}} + \mathbf{\Psi}_{\mathbf{FB}} \vec{\mathbf{B}}_{\mathbf{k}} \tag{2}$$

$$\vec{\mathbf{B}}_{\mathbf{k-1}} = \mathbf{\Psi}_{\mathbf{BF}} \vec{\mathbf{F}}_{\mathbf{k-1}} + \mathbf{\Psi}_{\mathbf{BB}} \vec{\mathbf{B}}_{\mathbf{k}} \tag{3}$$

Equation (3) may be solved for $\mathbf{B}_k$:

$$\vec{\mathbf{B}}_{\mathbf{k}} = -\mathbf{\Psi}_{\mathbf{BB}}^{-1} \mathbf{\Psi}_{\mathbf{BF}} \vec{\mathbf{F}}_{\mathbf{k-1}} + \mathbf{\Psi}_{\mathbf{BB}}^{-1} \vec{\mathbf{B}}_{\mathbf{k-1}} \tag{4}$$

which may be substituted directly into (2) to yield:

$$\vec{\mathbf{F}}_{\mathbf{k}} = [\mathbf{\Psi}_{\mathbf{FF}} - \mathbf{\Psi}_{\mathbf{FB}} \mathbf{\Psi}_{\mathbf{BB}}^{-1} \mathbf{\Psi}_{\mathbf{BF}}] \vec{\mathbf{F}}_{\mathbf{k-1}} + \mathbf{\Psi}_{\mathbf{FB}} \mathbf{\Psi}_{\mathbf{BB}}^{-1} \vec{\mathbf{B}}_{\mathbf{k-1}} \tag{5}$$

The matrix equation follows directly from (4) and (5)

$$\begin{bmatrix} \vec{\mathbf{F}}_{\mathbf{k}} \\ \vec{\mathbf{B}}_{\mathbf{k}} \end{bmatrix} = \begin{bmatrix} \mathbf{\Phi}_{\mathbf{FF}} & \mathbf{\Phi}_{\mathbf{FB}} \\ \mathbf{\Phi}_{\mathbf{BF}} & \mathbf{\Phi}_{\mathbf{BB}} \end{bmatrix} \begin{bmatrix} \vec{\mathbf{F}}_{\mathbf{k-1}} \\ \vec{\mathbf{B}}_{\mathbf{k-1}} \end{bmatrix} \tag{6}$$

with

$$\mathbf{\Phi}_{\mathbf{FF}} = \mathbf{\Psi}_{\mathbf{FF}} - \mathbf{\Psi}_{\mathbf{FB}} \mathbf{\Psi}_{\mathbf{BB}}^{-1} \mathbf{\Psi}_{\mathbf{BF}} \tag{7}$$

$$\mathbf{\Phi}_{\mathbf{FB}} = \mathbf{\Psi}_{\mathbf{FB}} \mathbf{\Psi}_{\mathbf{BB}}^{-1} \tag{8}$$

$$\mathbf{\Phi}_{\mathbf{BF}} = -\mathbf{\Psi}_{\mathbf{BB}}^{-1} \mathbf{\Psi}_{\mathbf{BF}} \tag{9}$$

$$\mathbf{\Phi}_{\mathbf{BB}} = \mathbf{\Psi}_{\mathbf{BB}}^{-1} \tag{10}$$

Equation (6) may now be used to analyze and design the two dimensional lattice filters. While we have found common denominators (poles) and other patterns, the analytic use of Eq. (6) is still an area of research for the proposing team. On the other hand, we have used numerical techniques to study several introductory cases. In Fig. 4, for example, is the transfer function in reflection for a simple 2x2 lattice bandpass filter showing a quality factor of approximately 75,000, which is adequate for the current generation of ITU grid DWDM fiber optic communications systems. Also shown is the tunability of the filter. The surface plot shows that the position of the peak may be shifted by adjusting the gains in the semiconductor optical amplifier, for fixed four directional coupler coefficients. This point is important because it demonstrates that the filter may be adjusted in a useful manner by the user, after fabrication. The tuning range is fairly modest, at approximately 20GHz (for a reasonable 1 THz FSR), and would require changing the current by approximately 4 mA. The tuning range will increase for filters of higher order. The filter theory also shows that the operation of this device will remain stable over this tuning range. In fact the filter theory is particularly convenient in describing stability; so long as the poles of the transfer function remain in the unit circle, no laser oscillation will occur.

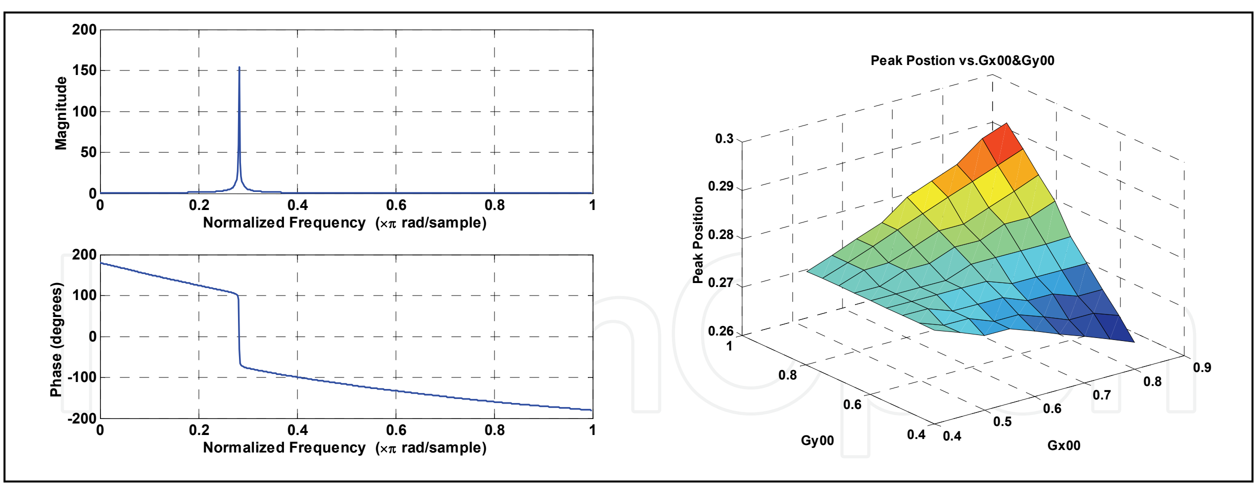

Fig. 4. Predicted bandpass behavior and gain tuning from a tunable two-dimensional active lattice filter.

In fact, there are several approaches to designing stable filters of high Q. In Fig. 10, a relatively "brute force" is taken to obtaining a high Q response with poles lying close to the unit circle. The position of the poles was chosen to account for error in the drive current to be one of the defining factors for the Q. A more thoughtful technique is shown in Fig. 11, wherein the bounded-input, bounded output stability criteria is used to define sheets of stability for a filter using a Newton-Raphson algorithm on the denominator of the transfer function (only one of several surface plots is shown). This stability criterion fixes the poles of a filter response, and provides a filter whose magnitude response is shown in the first Bode plot in Fig. 5. The second Bode plot in Fig 5 is the result optimized by then moving the zeros of the transfer function. The very sharp resonance is therefore determined in a manner that is inherently stable, since the zeros of the transfer function do not affect stability.

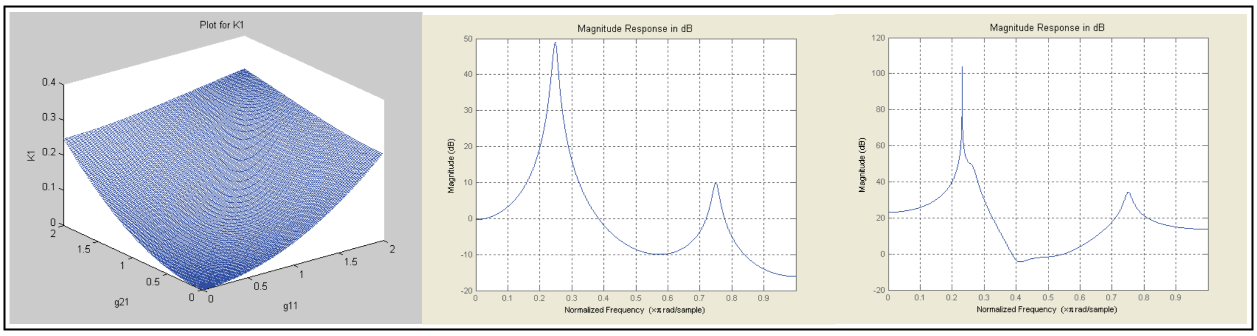

Fig. 5. Predicted bandpass behavior from a tunable two-dimensional active lattice filter. Stability is first set by the roots of the denominator, then the response is optimized by adjusting the remaining degrees of freedom in the denominator. The result is a very sharp filter resonance under fully stable operating conditions.

5. Conclusion

The photonics industry today is at a technically exciting and economically important juncture: The transition from discrete components to early, modest levels of integration. There are early indications of commercial promise for integrated photonics, including dedicated start-ups such as Infinera and Luxtera, and active development groups at large companies such as Intel. The current literature and prevailing views accept most of the basic lessons gleaned from the history of the electronic integrated circuit: the need for an integrated manufacturing platform, the value of chip real estate and overall yield. The role of gain is also well appreciated, especially in driving towards a scalable architecture. But gain also enables programmability, and therefore unlocks huge economic advantages of scale and scope. For example, the power to program microprocessors, DSPs, and FPGAs, allows the development and manufacturing costs of these devices to be amortized over a large number of "niche" applications with medium or small market sizes. The profitable "market of one" is achieved routinely by programmed microprocessors, digital signal processors (DSPs) and field programmable gate arrays (FPGAs). Since the same integrated circuit design may be used in a tremendous number of applications, the fixed costs of design, development and wafer fab can be amortized across disparate small markets. Further, it is quite common to re-program any of these integrated circuits remotely to improve performance or adapt their mission.

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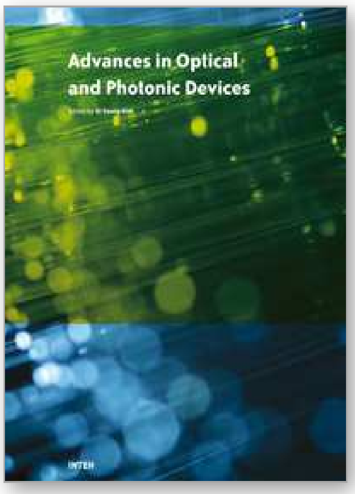

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The title of this book, Advances in Optical and Photonic Devices, encompasses a broad range of theory and applications which are of interest for diverse classes of optical and photonic devices. Unquestionably, recent successful achievements in modern optical communications and multifunctional systems have been accomplished based on composing “building blocks” of a variety of optical and photonic devices. Thus, the grasp of current trends and needs in device technology would be useful for further development of such a range of relative applications. The book is going to be a collection of contemporary researches and developments of various devices and structures in the area of optics and photonics. It is composed of 17 excellent chapters covering fundamental theory, physical operation mechanisms, fabrication and measurement techniques, and application examples. Besides, it contains comprehensive reviews of recent trends and advancements in the field. First six chapters are especially focused on diverse aspects of recent developments of lasers and related technologies, while the later chapters deal with various optical and photonic devices including waveguides, filters, oscillators, isolators, photodiodes, photomultipliers, microcavities, and so on. Although the book is a collected edition of specific technological issues, I strongly believe that the readers can obtain generous and overall ideas and knowledge of the state-of-the-art technologies in optical and photonic devices. Lastly, special words of thanks should go to all the scientists and engineers who have devoted a great deal of time to writing excellent chapters in this book.

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