Nanophotonic Integrated Circuit: A Platform for an "Optical Processor"

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Abstract

This whitepaper introduces a class of nanophotonic integrated circuits (nPICs), a platform technology for fiberoptic communication and computing, that is based on the natural index contrast (NIC) principle. Here I have laid down the basics of a multifunctional nanophotonic integrated circuit (nPIC) and a viable route to the fabrication of a PIC based "optical processor". The magic material "dendrimer" that enables the fabrication of the nPICs, is also described. In addition, a number of photonic band gap devices, based on the same basic process and material, are also described.

1. Introduction: NanoPhotonic Integrated Circuit (nPIC)

What is a nanophotonic integrated circuit (PIC)? By definition an integrated circuit (IC) is a microelectronic device that houses multiple circuits on a chip. For example, an IC is built by lithographic fabrication of numerous transistors on a silicon chip. Similarly a photonic IC is a device that houses integrated photonic functions on a chip. Although the physics of photon (a neutral particle) and electron or hole (charge carrying particle) are different that make an exact comparison a moot area, however, the evolutionary decades of the electronic IC does provide a positive outlook for the direction required for PICs. Paralleling the revolution of microelectronics, the development of PICs promises to increase functionality, density, and significantly reduced cost when compared to optical components assembled from discrete devices. While there are several clever existing technologies to design and build networks and systems, the fundamental breakthrough required to meet dramatically reduced cost points is the introduction of viable photonic ICs (PICs) technology that must meet the following criteria:

- The technology must be capable of creating a broad range of optical functions out of a single Fab or process.
- The means must exist for it to be readily manufactured at low cost in high volume.
- The capability must be developed to aggregate individual optical functions into more complex arrangements within the technology and with other optical technologies.

The last criterion is a major hurdle in the present day approaches. While investigation of many technologies is underway, ARP's efforts of monolithic integration show that its proposal meets these challenges, suggesting a clear first step towards viable PICs. In this technical note my aim is to discuss the main problems and proposed methods of solutions to those problems to achieve a PIC technology that can serve as a platform for the next generation of devices that will play crucial role in the fiberoptic communication, computing, and sensing.

While the classical computing has come a long way to the modern generation of fast computers and the Internet, yet there are problems and needs that require even faster speed, even higher bandwidth, and more importantly robust and cheaper methods of fabrication. Recently there has been an escalated effort in identifying better computing machines such as quantum computing, but those routes have their own set of problems and are far from realizing a tangible machine in the near future. In the photonics arena a wealth of research has resulted in a number of photonic devices as well, and those technologies are being used in fiberoptic communications, however, a true effort to achieve an integrated platform for optical communication and computing that can parallel the electronic counterpart is still missing. The optical components available today, be it passive, active, or a hybrid combination of the both, resemble the vacuum tubes that predate the modern transistors and ICs.

A long waited need is the ability to achieve a platform for integration of optics and microelectronics. Such capability can open the door to a new technology that is free from conventional microelectronics with low power, high bandwidth, and a higher speed, in the tera bits per second range. From the system integration perspective, there is a need for silicon based integrated devices. Silicon is a good candidate because not only it is a commonly used substrate for optical telecommunications devices, but also extremely matured in terms of processing, lending a means to integrate CMOS processes and photonic functionalities on a single chip. There has been a wealth of research that has mainly focused on passive integrated silicon devices. Silicon Single-Mode waveguides with less than 0.5mm cross-section have been demonstrated with loss of the order of 0.1 dB/cm. Extremely sharp curves, bands, and splitters have also been demonstrated, allowing a potential of higher level of integration. While these achievements are important and allows putting together the basic fiberoptic communication infrastructure, however, what could be considered as a parallel of the electronic ICs in the optics arena is still missing. This is primarily so because, silicon, as an optical material also poses several challenges that make it impossible to produce a true PIC that can replicate the IC revolution, as has been the history of the past decades. These issues are fundamental limitations that arise from material properties, and result in difficulty of externally controlling silicon structures for optical modulation and switching, and in a poor light emission from silicon devices due to silicon’s indirect bandgap, low electro-optic and low non-linear coefficient. There is a need to develop novel devices that can overcome the limitations of silicon based Photonics using novel materials and novel geometries, for enhancing the interaction of light with matter. Devices with novel functionalities that is compatible with silicon for switching, amplifying, and modulating need to be developed. Such devices will form the basis for an ultimate photonic integrated circuit.

PIC is an emerging technology that has a potential to address the above mentioned issues. However for a truly integrated photonic technology a smart material system is necessary that can function in a similar fashion as silicon can offer to IC technology. While the IC technology has come a long way to its present state of maturity, it is also blessed by the fact that at the fundamental level it only requires a periodic arrangement of numerous “transistors” (or p-n junctions) in a smaller dimension. Because its functionality depends primarily on the movement of charge carriers, the features necessary to carry out these functionalities can be as small as lithographically possible to fabricate, the latest being a 90nm line width.

Contrasting this with photonics, features suitable for photon guiding must first be able to accommodate the photons. As a result the waveguides must be of the order of the wavelength of the photon. This requirement is, in fact, an advantage for photonics because lithographic processes are readily available. On the other hand there is a new set of challenges because of the difficulties explained above, and because of the fact that silicon can not do everything necessary to do photon manipulations. From a fundamental point of view the basic functionalities necessary to build a chip that can ultimately be termed as an “optical processor” are: guiding, amplifying, modulating, signal processing, attenuating, sensing, on-chip light source and detector, and inputting and outputting of the signal. Being able to build all of these functionalities on a single chip that would represent a true PIC, is an ambitious goal. Nevertheless, this is what one must be able to achieve in order to make it a breakthrough not only from a scientific and technology point of view, but also to be able to solve the problems that are outstanding.

2. Dendrimer Based Nanophotonics

ARP Inc is introducing a novel material system for photonic fabrication that can achieve much of the above functionalities. The “magic” material is a new class of polymer that offers characteristics unparallel to any other material in a single platform. These are called dendrimers [1-3] that are a spherical molecule having the flexibility of tailoring its physical properties while the fabrication process for different functionalities remains relatively unchanged.

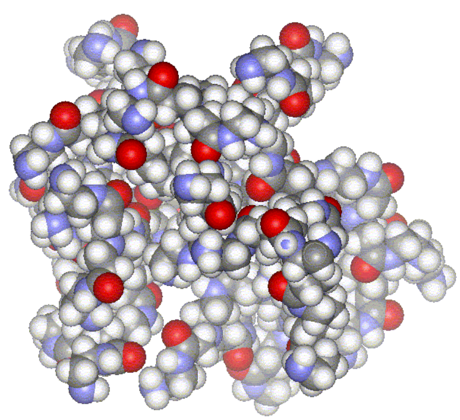

Fig. 1. 3-D visualization of a PAMAM (G3) dendrimer molecule.

ARP has discovered that dendrimers (e.g., poly(amido amine), PAMAM) can be used to design photonic waveguide and bandgap structures to produce robust PICs while simultaneously simplify the processing. Dendrimers possess some attractive advantages not available in other materials. First, a single material platform for multiple optical functionalities: waveguiding, amplifying, modulating and bandgap. Combining these properties with ARP’s unique design will enable significant performance improvement and size reduction over traditional routes. Second, dendrimer can be deposited on to silicon wafers using common techniques such as spin casting. Third, these films can be processed using common processes such as dry etching. Finally being able to cast and pattern dendrimers on silicon substrate is a big plus, because, it opens the door to integrate photonics with electronic functionalities via CMOS processes. Thus dendrimers offer a cheaper, higher performance, manufactureable, and easy transition to production route for the PIC development.

Dendrimer distinguishes itself from other materials because of the fact that they offer properties suitable for multiple optical functionalities in a polymeric form while processing is significantly simpler. Dendrimers are three-dimensional, core-shell structured polymers that come in nano-scale dimension for the proposed application. They are monodispersed polymers with spherical molecular architecture. Their structure is characterized by three distinct features: (i) a central multifunctional core, (ii) tiers or "generations" of multifunctional repeat units (substituents) attached around the core, and (iii) terminal or end groups that are also multifunctional. Manipulating these three features allows controlled synthesis of a series of end-functionalized macromolecules whose physical properties can be tailored to instill different photonic functionalities.

Dendrimers' molecular dimensions range from 1.4 nm (G0) to 11.4 nm (G9) [1], making them very suitable for nano-scale fabrication. Fig. 2 shows a photomicrograph of ridge waveguide patterns produced by our group on G4 PAMAM dendrimer film via reactive ion etching. Lines of different widths have been etched on spun-on, cured dendrimer film on a silicon substrate. Using the modern tools available at the PennState Nanofabrication Facility, features as small as 20 nm can be designed.

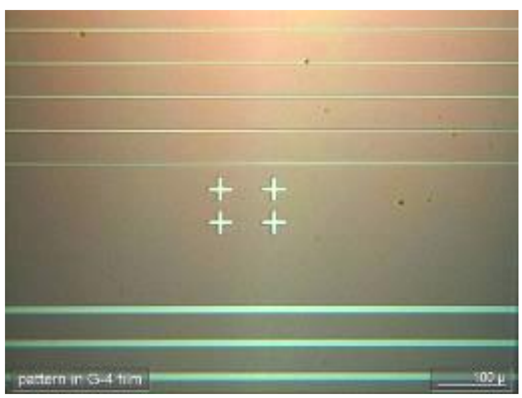

Fig. 2. Photomicrograph of ridge waveguide patterns on G4 PAMAM dendrimer film produced via reactive ion etching. Lines of different widths have been etched on spun-on, cured dendrimer film on a silicon substrate. Four fiducial marks (plus sign) are also visible.

Dendrimers can also be used to design Photonic Band Gaps (PBGs) that has the potential for fabricating ultra miniature photonic components with tailored properties [4–5]. Manufacturable PBG structures are important for many applications, especially, where precision guided wave is involved. Fig. 3 shows a sketch of a PBG based interferometer proposed by ARP. Here PBG waveguides are used to build the "arms" of the interferometer, and selective coating on one arm is used to probe selected chemicals for sensing. Successful development of photonic crystal interferometer will have application in various sensing such as chemical and biological species identification.

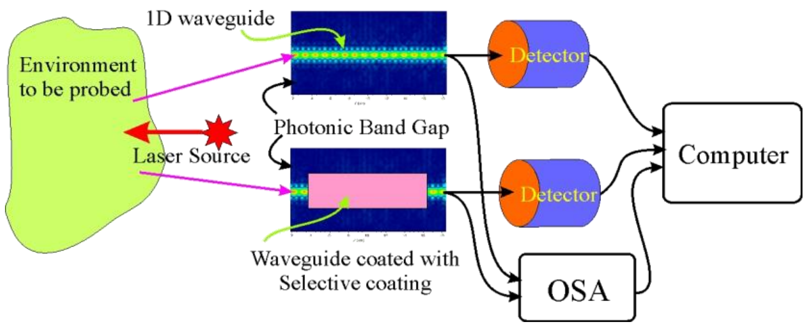

Fig. 3. Conceptual construction of a Photonic Crystal Interferometer. The 1-D waveguide is created by a line-defect in the bandgap. The intensity distribution is obtained via simulation (not in scale).

3. Route to PIC Fabrication

Integrated photonic devices typically consist of nano-scale structures, with individual feature sizes controlled to dimensions ranging from few microns to few tens of nanometers. These devices are manufactured on a wafer scale in a semiconductor-like manufacturing process that results in optical chips in sizes from 1x1 mm to tens of millimeters. The first step in realizing a PIC device is to design the structure that yields the desired optical properties. That can be done through a combination of simulation and prototyping. Once a design is finalized, various lithography techniques, including reactive ion etching and e-beam lithography, can be used to fabricate the devices in batch.

3.1. Monolithic vs. Hybrid Integration

Because of their physics and the manufacturing process may differ for different materials system, photonic structures can be integrated in multiple ways, both with themselves on a chip (monolithic integration) and with other structures and processes (hybrid integration) to produce a variety of photonic devices. ARP's main thrust is on the monolithic integration; because, only this route is capable of producing highly reliable devices in the lowest possible geometry and cost bracket.

When processing a single beam of light (or multiple beams identically, e.g., a splitter or a thin-film interference filter), the task is rather straightforward integration that can be achieved by simple sequencing of optical functions. However, for a monolithic integration of multiple parallel beams of light in a single device (e.g., a RAWG), the design can be accomplished by using an array of differing optical functions on a single horizontal layer. An art-work consisting of an array of nanophotonic functions is created by using masking and lithography steps. This is conveniently achieved by thin-film patterning processes.

In a broad range of optical components, the incident optical beams are split into constituent beams, which are differentially processed, passed through suitable mechanisms such as a waveplate or a wedge to compensate for introduced polarization difference, and then either recombined or allowed to undergo controlled interference. The resulting benefit is a compact, monolithically interconnected array of optical functions that can be packaged much more easily, resulting in increased density and reduced manufacturing costs.

4. Steps in Monolithic Multifunction Fabrication

4.1. A Method of Monolithic Integration

ARP has been working at the PennState Nanofab [6] and Dendritic NanoTechnologies [1] to build photonic integrated circuits on silicon wafer from dendrimer based waveguides. Preliminary results demonstrate that dendrimer based waveguide can be fabricated by techniques such as spin-coating and dry etching method. However, there are challenges that must be addressed to arrive at a robust method for monolithic integration of different functionalities.

A monolithic integration of multiple functionalities on a chip involves construction of photonic integrated circuit (e.g., see Fig. 4) that is composed of mux/demux, an amplifier, and/or a modulator for each channel; all connected via waveguide interconnect and with appropriate input/output. While dendrimers, modified for different functionalities, make it possible to obtain all of these functionalities, however, currently no method exists for fabricating these functionalities on a single chip. We envision an integrated design where a single mask will be used to layout all components including waveguide interconnects. While a scheme of this magnitude is naturally challenging, however, here in lies the opportunity to build a true photonic integrated circuit that can pave the road for the next generation of fiberoptic communication and computation on an integrated platform. The ability of accomplishing the above will lay the foundation for achieving a “system-on-a-chip” or an “optical processor” that in addition to passive, amplifying, and modulating functions, will also house laser source and detector on the same chip. Also via a smart coupling scheme these chips can be packaged in a similar fashion as the ICs are packaged on a PCB board.

4.2. Photonic waveguide: In search of an optical transistor

As outlined before, photonic waveguide is the basic "building block" of photonic integrated circuits that are somewhat analogous to the transistors in the electronic IC. As mentioned before, although the physics of photon and electron/hole are different that make an exact comparison between the PIC and electronic IC unwarranted, nevertheless, waveguide can be designed to process optical signal in many ways as transistors can process electronic signals.

Consider a common application of a PIC, the wavelength division multiplexing (WDM) and demultiplexing on a chip, commonly known as an arrayed waveguide grating (AWG) or a PLC. Such a PIC can be accomplished by assembling waveguides in the form of a grating. A PIC, however, may combine more functionalities than just light guiding, provided, waveguide can be designed to perform a number of optical functions mentioned before (amplification, modulation, switching, etc.), thus allowing it to be analogous to a transistor. Also, using the PICs as a basic building block, a number of photonic devices then can be constructed to carry out various photonic signal processing.

For a waveguide to act more like a transistor, one ought to be able to design it such that it can carry out the tasks with photons as a transistor does with electrons. To begin with we envision a chip that will guide and amplify the photons. In addition, with the help of a smarter design it will also modulate photonic signals on the same chip. To accomplish these three functionalities by means of monolithic integration one ought to be able to find a material system that can be processed synergistically without requiring multiple processes at each step. While silicon has adaptability towards waveguiding and amplifying, however, owing to its indirect bandgap and poor electro-optic properties it is not suitable for modulation. Dendrimer, on the other hand, can be made suitable to obtain all three of these functionalities. However, there are new challenges in working out a scheme that would allow one to accomplish the integration process. To this end we have conceptualized a method that would work in the following way.

Here waveguide will be designed where the core material is composed of amplifying dendrimers which is also suitable for modulation. Dendrimer can be doped with fluorescing rare-earth metal ions to instill amplification. They can also be doped with elements to increase its electro-optic coefficient. So the task, as it stands, is to design a dendrimer material that will both be amplifier and modulator while simultaneously satisfying the requirements of a waveguide. And it is possible for dendrimer to do just that. In other words, a dendrimer will be designed such that under appropriate condition its property will be either an amplifier or a modulator. A clever design will ensure that the right functionality is instilled in the right segment of the circuit.

Some basic research, however, is necessary to investigate the amplification efficiency and modulation efficiency of dendrimers. While schemes of doping are known, yet not a lot of data are available to get a quantitative feeling. Therefore, one first needs to carry out this basic research to obtain the baseline data and then adjust the dendrimer properties for optimum performance.

Obviously, the efficiency of amplification and modulation will be proportional to rare-earth attachment level which will depend on the size and chelating capability of the specific dendrimer molecule. For example, with increasing dendrimer size (i.e., higher generation), the number of sites per dendrimer molecule increases rapidly (e.g., $2^{(n+2)}$ for EDA core PAMAM dendrimer). The efficiency of metal attachment, therefore, is controlled by dendrimer generation. The fluorescence wavelength can be tuned by choosing a suitable rare-earth metal. For example, Erbium will fluoresce in the 1500–1600 nm range (see Fig. 6), Neodymium will fluoresce in the 1060 nm range, Praseodymium will fluoresce in the 1250–1300 nm range, Thorium and Holmium will fluoresce in the 1300–1400 nm range, and Terbium will fluoresce in the 1400–1500 nm range. Depending on the wavelength range, amplification between 5 dB to 30 dB can be achieved.

4.3. Design and simulation of multifunctional PIC chip

A monolithic integration scheme will involve the following: (i) to obtain optimum structure of a multicahnnel reflective arrayed waveguide grating (RAWG) used as a mux/demux, (ii) to obtain an optimum geometry and amplification parameters for an amplifying block suitable for monolithic integration with the RAWG module, (iii) to work out pump configuration for the combined module, (iv) work out interfacing scheme for signal in and out, and (v) overall design of a chip accommodating items (i)–(iv) via on-chip waveguide interconnect. While many of these items are straightforward individually, however, obtaining an optimized integrated model of the overall chip layout poses significant challenge as this require adapting each function in its own domain as well as functioning with others in technical harmony.

4.4. Scheme for monolithic integration of different functionalities

Example of integration schemes are shown in Fig. 4. Fig. 4 (a) shows a scheme for loss-less RAWG lay out where an amplifier block and a RAWG is laid on a chip via waveguide interconnect and Fig. 4 (b) shows a scheme for adding a modulation unit per channel of the RAWG along with an amplifying block. Other functionalities such as MEMS can also be added with appropriate layout scheme.

Here individual structures are first optimized via simulation and then organized by “geometry optimization” procedure.

ARP, in collaboration with the Dendritic Nanotechnologies Inc. (DNT) is designing experiments in preparation of PIC fabrication from dendrimer. From initial trials we have found that optical grade dendrimer films can be deposited on silicon substrates by spin casting method. Further we have found that deposited film’s refractive index can be varied by chemical treatments as well as by varying the generation of dendrimer. For instance, refractive index of PAMAM G4 film was measured to be 1.485 after curing. When this film was immersed in acetone for two minutes and rinsed by isopropanol alcohol, its refractive index increased to 1.506. Our preliminary experiments also showed that PAMAM G0 and G4 films refractive index differential are suitable for waveguide cladding and core formation.

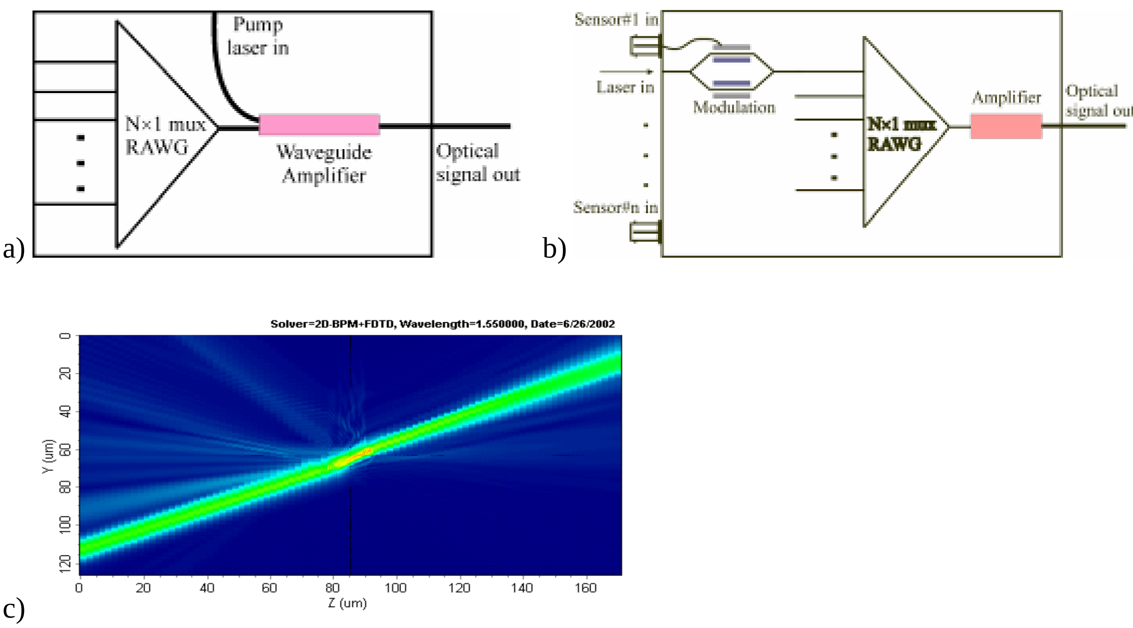

Fig. 4. (a) A PIC with second-phase integration of a mux/demux with an amplifying block, (b) an example of triple-phase integration where a mux/demux is integrated with an on-chip modulator and an amplifier block, all monolithically integrated with waveguide interconnect, and (c) a MEMS block simulated with APSS [8].

5. Background Research on Dendrimer Nanophotonics

5.1. *Dendrimer Waveguide*

Dendrimers form smooth films on many substrates. We have investigated film forming properties on Gold and Silicon substrates and found that optical quality films can be produced by spin casting method. While deposition of dendrimer on Gold was carried out for a fundamental investigation of adsorption mechanism of these macromolecules, however, by means of these experiments we discovered that the film thickness is an exponentially increasing function of dendrimer's generation [7]. Fig. 5 (a) shows the frequency response of a quartz crystal resonator for adsorption of dendrimer as a function of its generation. Fig. 5 (b) shows the equilibrium frequency shift at saturation corresponding to generation numbers. As can be seen from Fig. 5 (b), dendrimer film thickness increases exponentially as a function of generation for the first six generations. Because of the thickness variation and other molecular arrangement differences, refractive index also varies as a function of dendrimer generation, which forms the basis for what is termed as "natural index contrast" or NIC principle for waveguiding.

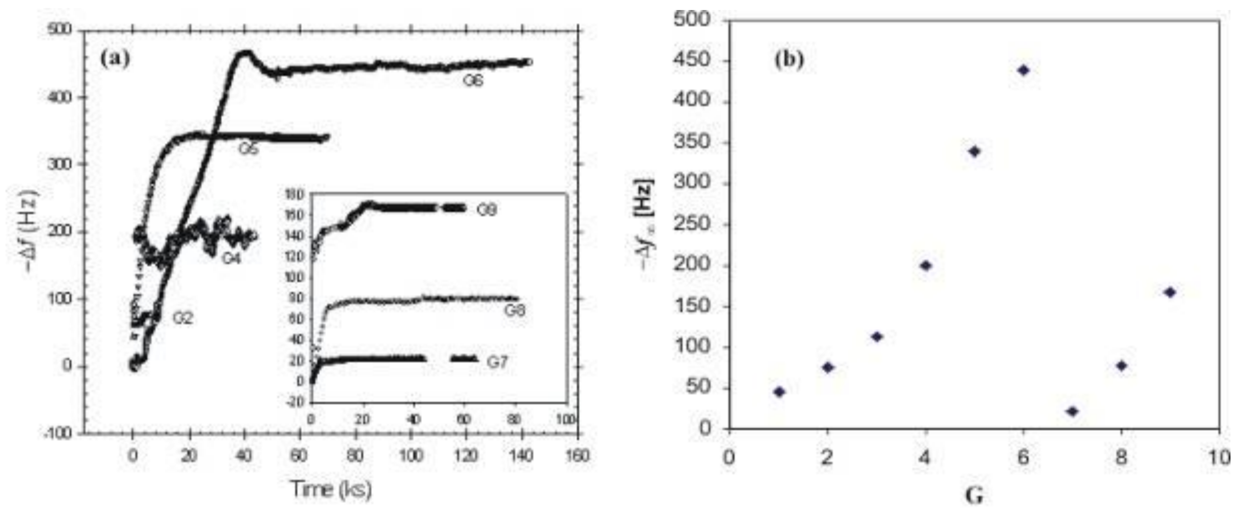

Fig. 5. (a) Frequency shift during dendrimer adsorption on gold and (b) frequency shift at equilibrium vs. generation (adapted from Ref. 5).

Moreover, dendrimer thin film's refractive index within a given generation can be controlled by factors such as choice of center-molecule, shell-structure (substituent), and doping the molecule with alkali atoms. For the waveguide confinement zone (core) characterized by a higher refractive index (RI) that is covered by a cladding of slightly lower RI, dendrimers make a good choice. It has been reported that fluorinated dendrimers have a RI in the range of 1.528–1.536 for wavelengths ranging from 1320 nm to 1550 nm [8].

Further, dendrimer can also be doped with rare earth fluorescent atoms to tailor its property for optical amplification and modulation, as mentioned before (also see in later sections). Thus, there are several ways that appropriate waveguide core and cladding layers can be created from dendrimers. The method is termed as "natural index contrast" or NIC principle because, here the built-in index differential is used for waveguiding. For example, we measured the refractive index (RI) of spun-on dendrimer films on silicon wafer using a Gaertner L116C ellipsometer. It was found that the RI of G0 film n_0 = 1.463 while the RI of G4 film n_4 = 1.511, exhibiting a NIC value of $\Delta n = \frac{n_4 - n_0}{n_0} \times 100$ = 3.28%. Thus one can use G0 film as the cladding and the G4 film as the core of the NIC based waveguide from dendrimer films.

5.2. Dendrimer Amplifier

As described before, dendrimers can be doped with fluorescing rare-earth metal ions via liquid phase chemistry such as chelation. It was reported by Pitois et al. [8] that they used certain dendrimers to produce optical amplification with Nd^{3+}, Pr^{3+} and Er^{3+}. For illustration purposes their data are shown in Fig. 6. However, using a method discovered by Tomalia group [1] one can produce a number of amplifying dendrimer. The wavelength range for amplification will depend on the rare-earth metal incorporation. For example, doping with Erbium will amplify in the 1500–1600 nm range (see Fig. 6), Neodymium will amplify in the 1060 nm range, Praseodymium will amplify in the 1250–1300 nm range, Thorium and Holmium will amplify in the 1300–1400 nm range, and Terbium will amplify in the 1400–1500 nm range. A gain curve obtained via simulation from G2 dendrimer is shown in Fig. 7.

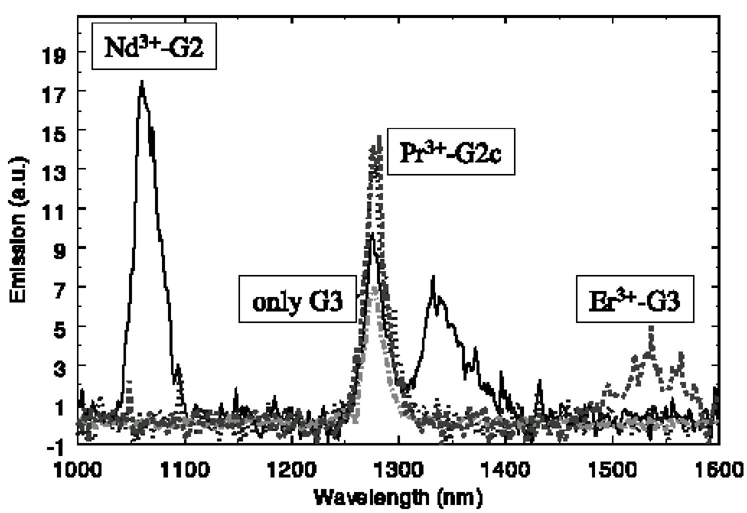

Fig. 6. Emission spectra of Nd^{3+}-G2, Pr^{3+}-G2, Er^{3+}-G3 and bare G3 (adapted from Ref. 8).

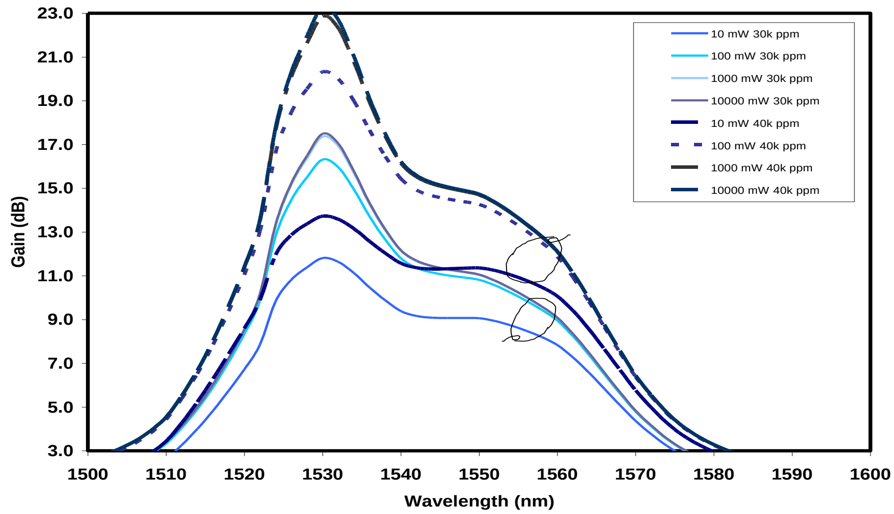

Fig. 7. Gain from dendrimer based waveguide amplifier (via simulation). © ARP Inc.

5.3. Photonic band gaps and optical modulation

Another attractive use of dendrimer is to produce optical modulator and photonic band gaps (PBGs) on silicon wafer. It has been shown by Hawker et al. [9] that the dielectric constant of dendrimers can be tuned by blending dendrimer with higher dielectric constant molecules (see Fig. 8). PBGs have been produced from low dielectric constant polymers [4–5] and therefore, dendrimer alone can be used for PBG fabrication (see examples in Fig. 9), however, one can also tune its dielectric properties over a range by chemical blending. The electro-optic coefficient can also be modified in a similar fashion. Several ideas are under consideration and will be tested as we progress.

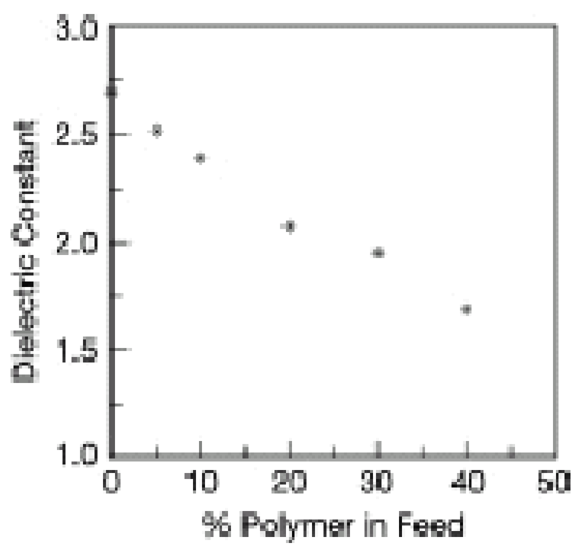

Fig. 8. Dielectric constant versus weight percent of blending agent in blended dendrimer (adapted from Ref. 9).

6. Device Design and Simulation

The following are examples of some results based on ARP's design of PICs. In particular, results of RAWGs and photonic band gap based devices are briefly presented here.

6.1. Waveguide

As stated before, waveguides are the basic constituent elements of the PICs. Fig. 8 shows a design and simulation results of a waveguide section constructed from dendrimer on silicon substrate. This demonstrates that dendrimer satisfies the physical requirements for waveguide fabrication. Also one can form thin films with dendrimer and cured dendrimer films are suitable for common fab process; this satisfies the chemical requirements.

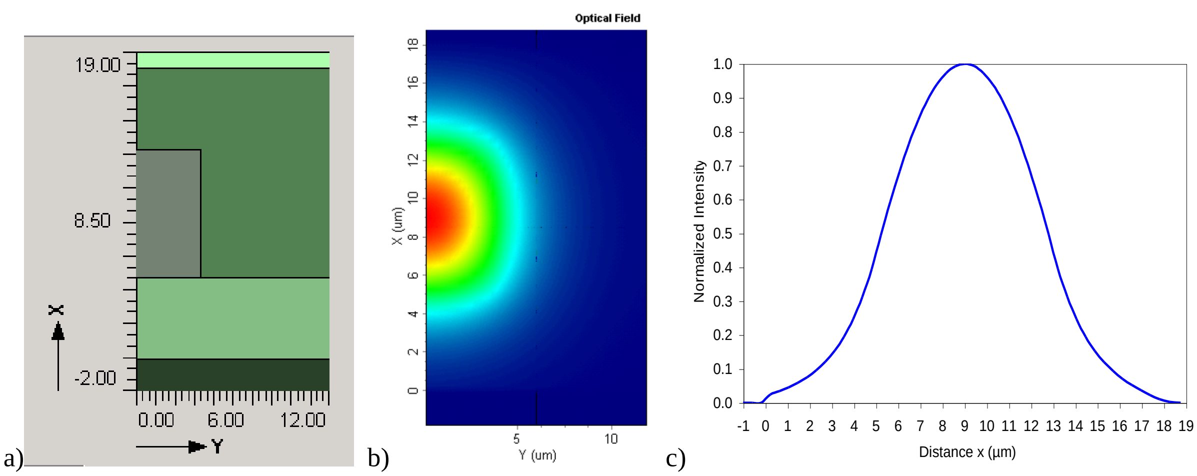

Fig. 8. Waveguide section geometry and its simulated mode filed: a) section with half core-width showing, different shade indicates different index material; b) 2-d mode field; and c) normalized field-intensity along x-axis, the peak corresponds to the center of red spot in (b).

6.2. Arrayed Waveguide Grating

Arrayed waveguide grating is an important PIC that is constructed from waveguide elements. Here, the results of AWG designed from the aforementioned waveguides are shown for an eight channel TAWG (Fig. 10) and RAWG (Fig. 11). The results show a lower loss for the RAWG compared to the TAWG for identical material and waveguide parameters. AWGs are attractive for its higher channel count and lower channel spacing properties. Up to 48 channels can be accommodated on a single chip without losing size vs. performance and cost advantages. Some details of AWG design and characterization is given in the following web pages: http://dwdm2.home.comcast.net/awgrating.html and http://dwdm2.home.comcast.net/awg_characterization.html.

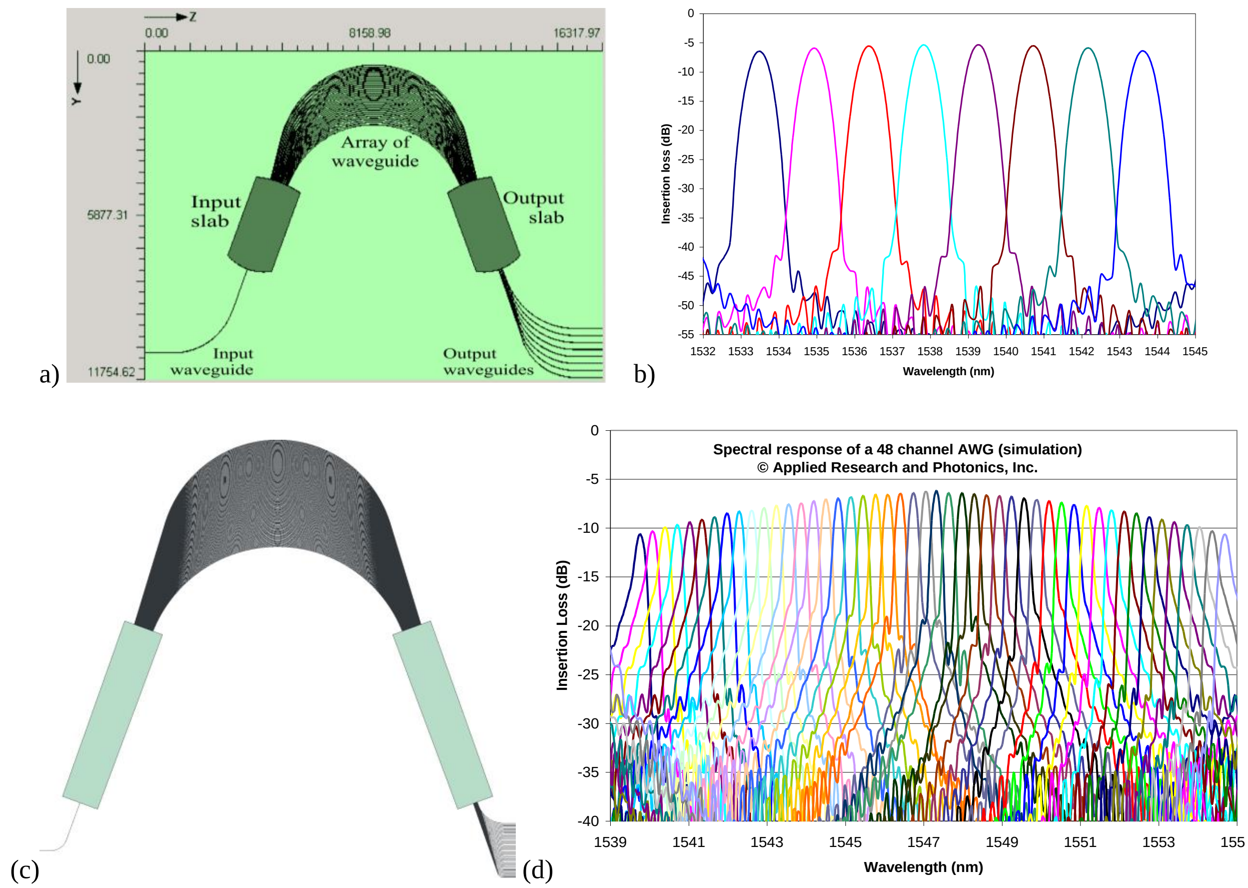

Fig. 10. (a) A conventional transmissive AWG (TAWG) with an input slab (left) and an output slab (right), (b) its spectral response. (c) A 48 channel TAWG and (d) its spectral response. (Design and simulation done by APSS).

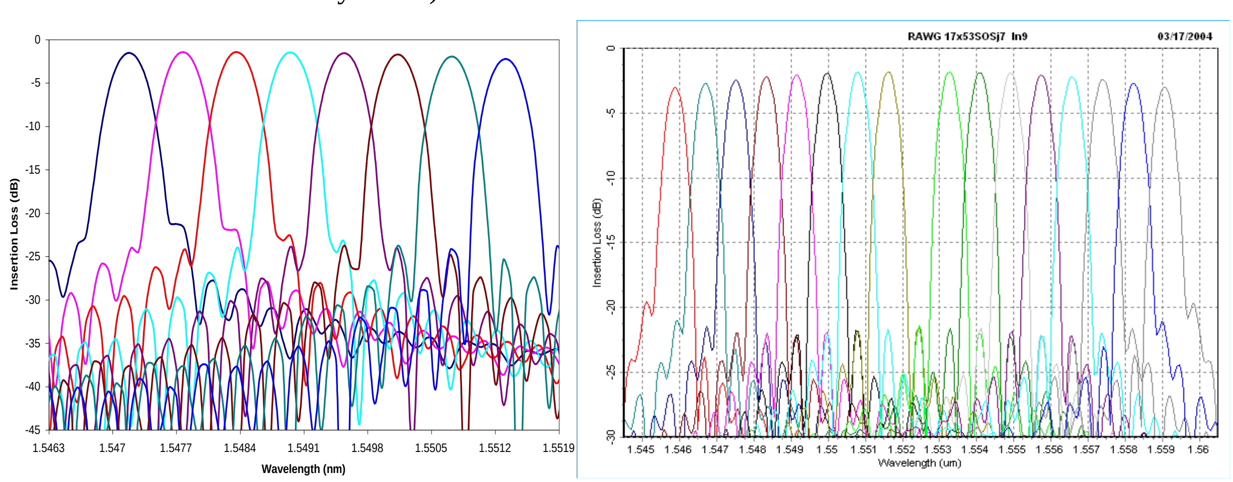

Fig. 11. Simulation of Reflective AWG (RAWG) with a single slab, designed from dendrimer waveguides. Spectral response of (a) an 8-channel and (b) a 16-channel RAWG.

6.3. Photonic Band Gaps

Fig. 12 shows design and simulation of several devices from dendrimer based photonic band gaps (see figure caption for a brief description).

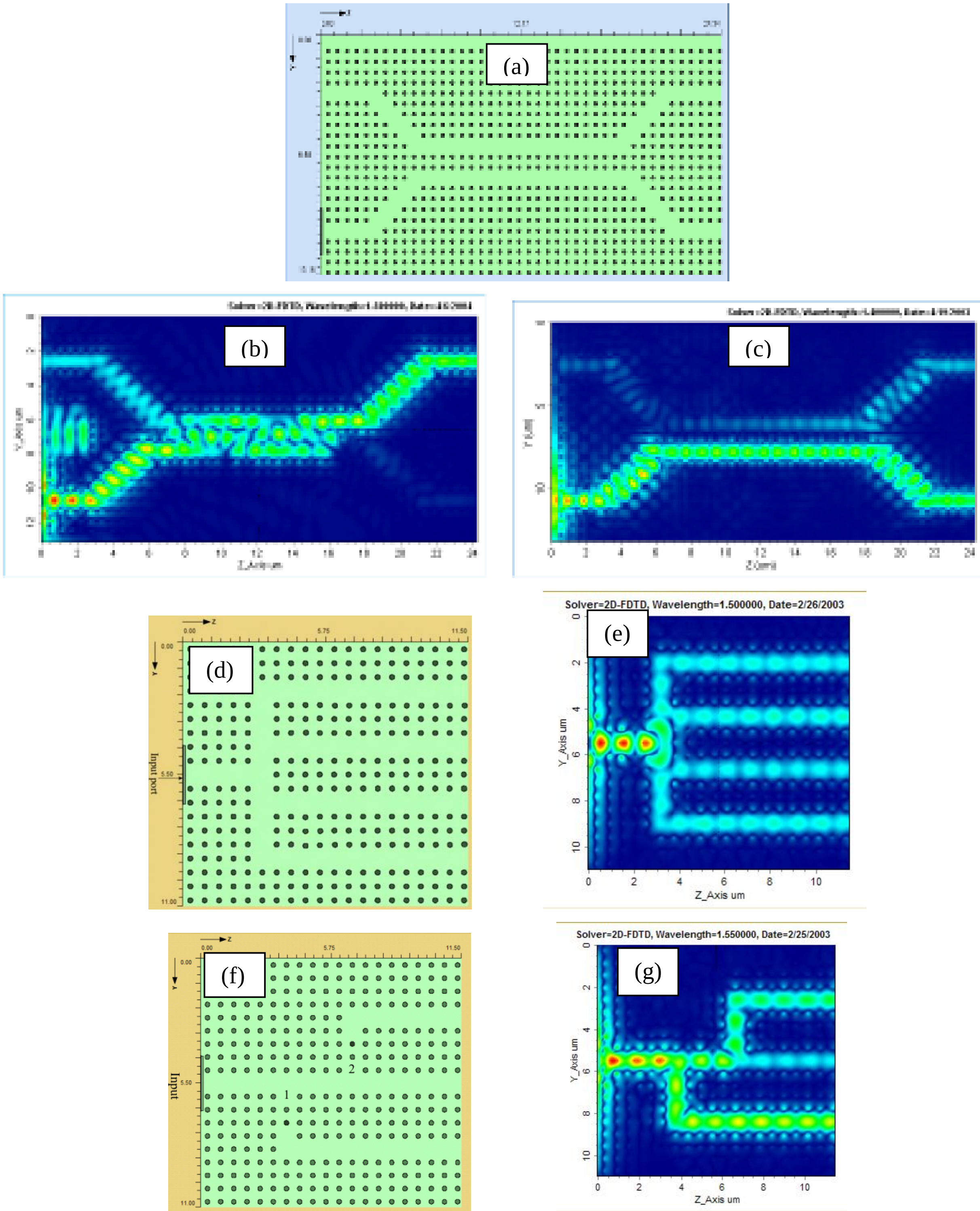

Fig. 12. Design and simulation of photonic band gap devices from dendrimer. (a) A directional coupler, (b) & (c) are wavelength dependent outputs from (a) that exhibits switching property, (d) miniature 1×4 splitter (11 µm), (e) energy propagation through the splitter exhibiting 90° bend waveguiding, (f) miniature 1×2 demux (11 µm) where wavelength selection is achieved via size ad index variation of impurity lattice, and (g) output from demux. Simulation was done with APSS [10].

7. Summary

In this article I have laid down the basics of a multifunctional nanophotonic integrated circuit (nPIC) and a viable route to the fabrication of PIC based "optical processor". In addition, a novel material, dendrimer, has been introduced to address many barriers to PIC fabrication. Dendrimer is able to offer multiple photonic functionalities to a PIC, in a similar way that silicon can offer to the electronic ICs. Further, dendrimer offers a simpler fabrication route rendering a robust, cost-effective, and manufacture able route to the PIC. Further, dendrimers can also be used to fabricate photonic band gaps. This ability opens the door for further miniaturization of PICs. Last but not least, dendrimer offers the potential for integration of nPIC to CMOS processes that will open the door to a "system on a chip" for an optical processor.

8. Acknowledgement

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