# Overview of Silicon Photonic Signal Processing

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## Abstract:

**As we move steadily into the world of compact and ultrafast devices, there is a steady increase in demand for high speed devices and gadgets. Here, photonics comes handy and even more with the advent of Silicon Photonics, which enables photonics and electronics to be integrated into the same chip. In this paper, two all optical systems, one an all optical processor/multiplier based on second harmonic generation and another, a Radio Over Fibre communication system are presented. . These techniques would be potential contenders in revolutionizing the world of Telecommunication and signal processing, effectively replacing electronics with photonics, which would result in extremely fast devices and reduced thermal effects.**

## 1 Objective:

The main objective of this paper is to outline some fundamental concepts regarding silicon photonics and photonic crystals, and then present design issues and applications for a photonic based Mobile Communication system(RoF) and an all optical multiplier/processor based on Second Harmonic Generation.

## 2 Introduction:

### 2.1 Photonics:

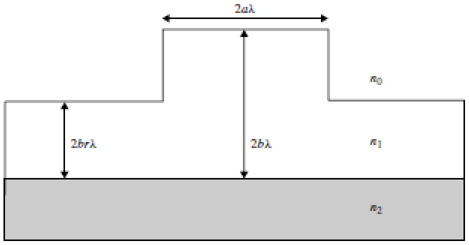
The science of photonics includes the generation, emission, transmission, modulation, signal processing, switching, amplification, detection and sensing of light. The term photonics thereby emphasizes that photons are neither particles nor waves — they are different in that they have both particle and wave nature. It covers all technical applications of light over the whole spectrum from ultraviolet over the visible to the near-, mid- and far-infrared.

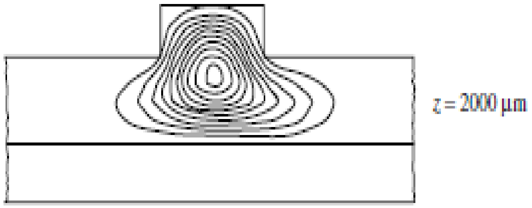
### 2.2 Silicon Photonics:

**Silicon photonics** refers to photonic systems which use silicon as an optical medium. The silicon typically lies on top of a layer of silica in what is known as **silicon on insulator**(SOI).

The propagation of light through silicon devices is governed by a range of nonlinear optical phenomena such as the Kerr effect, the Raman effect, two photon absorption and interactions between photons and free charge carriers. Silicon is transparent to infrared light with wavelengths above about 1.1 micrometres. Silicon also has a very high refractive index, of about 3.5. The tight optical confinement provided by this high index allows for microscopic optical waveguides, which may have cross-sectional dimensions of only a few hundred nanometers.

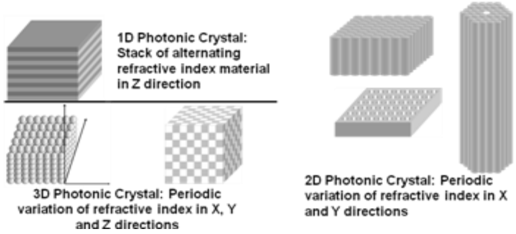
The main advantage of silicon photonics is that silicon photonic devices can be made using existing semiconductor fabrication techniques, and because silicon is already used as the substrate for most integrated circuits, it is possible to create hybrid devices in which the optical and electronic components are integrated onto a single microchip. Shown below is the structure of a typical Silicon Photonic (SOI) Waveguide, popularly calles a Rib Waveguide.





## 2.3 Photonic Crystals:

Photonic Crystals are produced by periodically varying refractive index in one, two or three dimensions. The period is comparable to the wavelength of light. Thus the field of Photonic Crystals can be looked upon as Microphotonics. However, in order to fabricate Photonic Crystals with micron-scale period, the fabrication technique must have nano-scale resolution. Thus it is appropriate to include Photonic Crystals in studies of Nanophotonics. Figures below show schematic representations of 1D, 2D and 3D Photonic Crystals.



In Nature, parts of several living organisms have Photonic Crystals in them. Iridescent colors of butterfly wings and peacock feathers are due to Photonic Crystals. Photonic Band Gap crystals have several photonics-related applications, including microlasers, and waveguides/ waveguide-couplers, photonic band-gap optical fibers with novel dispersion characteristics etc.

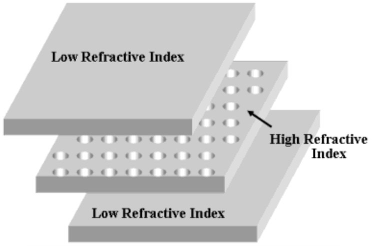
The most striking similarity is the Band-Gap within the spectra of Electron and Photon Energies. Solution of Schroedinger's equation in a 3D periodic coulomb potential for electron crystal forbids propagation of free electrons with energies within the Energy Band-Gap. Likewise, diffraction of light within a Photonic Crystal is forbidden for a range of frequencies which gives the concept of Photonic Band-Gap. The forbidden range of frequencies depends on the direction of light with respect to the photonic crystal lattice. However, for a sufficiently refractive-index contrast (ratio n1/n2), there exists a Band-Gap which is omni-directional.

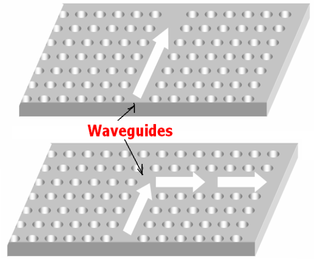
Band-Gap frequencies when incident on the photonic crystal will be not be transmitted but be reflected/diffracted . Optical characteristics of Photonic Crystals can best be understood by plotting the Dispersion Curve, i.e. variation of frequency ($\omega$) of light with components of its wave-vector (k). Similar dispersion curves in Electronic Crystals, i.e. variation of energy E with k of electrons reveal the Electronic Band Gap.

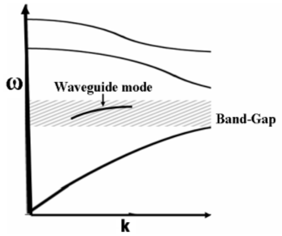
Prism effect refers to separation of colors by refraction through a prism. This is related to dispersion or variation of refractive index with wavelength. In a normal bulk medium like glass, dispersion is small. Prism effect is related to the derivative ($dn/d\lambda$) of refractive index with wavelength. This derivative can be made unusually large in photonic crystals. Photonic crystals can also exhibit an effective negative refractive index as explained below. This effect is seen in photonic crystals in the microwave and visible regions of spectrum.

The applications of Photonic crystals are as follows:

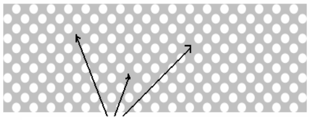
1. 2D Photonic crystals have a potential for fabricating waveguides and related components for integrated optics. Unlike the conventional refractive planar waveguides, these work by diffraction. Modes that cannot propagate through the 2D photonic crystal lattice (i.e. those within the band-gap) can propagate easily within the waveguides, including those waveguides which have a sharp bend at right angle.





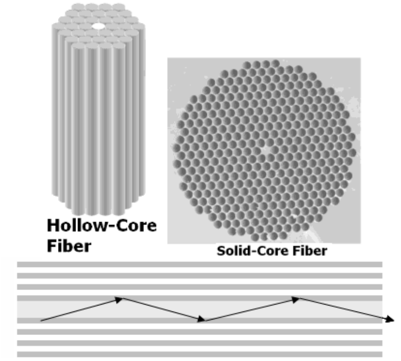


2. Defects in a Photonic Crystal Lattice produce microcavities which have size-dependent radiation modes. Just like electronic crystal these produce defect-states in the Band-Gap. Microcavity is resonant for wavelength $\lambda$, satisfying, $D = N(\lambda/2)$, where N is an integer and D, the characteristic size of the cavity. Microcavity lasers have been fabricated by this technique.



**Defects in a Photonic Crystal**

3. Photonic Crystal Optical Fibers are a special class of 2D photonic crystal where the dimension of the medium perpendicular to the crystal plane could be 100s of meters long. These are known by several names: Photonic Crystal Fiber , Photonic Bandgap Fiber, Holey Fiber, Microstructured Fiber and Bragg Fiber. Frequencies in the Band-gap propagate within the fiber-core, which is like a defect in 2D photonic crystal. Hollow-core fibers have several advantages as compared to the conventional solid-core fiber. While hollow-core photonic band-gap fibers work by diffraction, solid-core photonic band-gap fibers work by both internal refraction as well as diffraction.
4. Since light travels in air, group velocity dispersion can be zero for all wavelengths.
5. By filling the hollow-core with gas, the fiber can be used as a very sensitive gas sensor.
6. In hollow-core, even those wavelengths can propagate which have high loss in conventional fibers. Propagation for ~1000 m has been shown for wavelengths like 1.5 micron and 10 micron with an attenuation of around ~ 1dB/km.



Propagation by Bragg-Diffraction

## 3 Photonic Device Design Procedure:

The following steps give the procedure to be followed while designing a photonic device.

1. The device structure and dimensions are determined and sketched.
2. Computational Electrodynamic techniques are then used in either frequency domain (Finite Element Method(FEM)) or time domain(Finite Difference Time Domain(FDTD)) to solve the Maxwell's Electromagnetic equations and arrive at the solutions and hence compute the mode fields (TE and TM modes).
3. From the mode fields, the various characteristics of the device such as refractive index, wavelength sensitivity etc has to be plotted.
4. Then various linear effects like attenuation and dispersion and nonlinear effects such as Kerr effect, Self phase and Cross phase modulation, Two Photon absorption etc should be studied.
5. Finally the design is over and the structure is sent to the Fabricating unit to fabricate the photonic device.

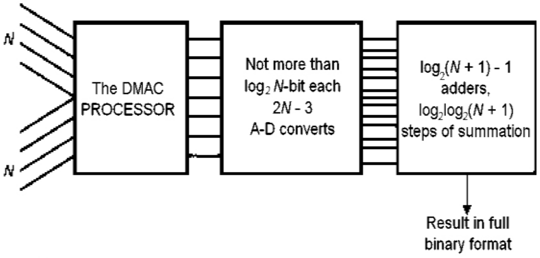
## 4 Design of an All-Optical Multiplier:

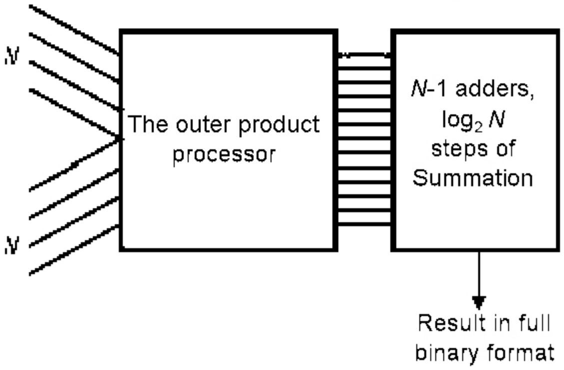
### 4.1 DMAC Algorithm and the Outer Product algorithm:

Vector-matrix multiplication is the primary operation which is exploited, for example, in finding the unequivalency function for an associative search in a memory system or which is applied in the central processor of a digital computer. All optical components for multiplication can be implemented by using various nonlinear phenomena via non-collinear second harmonic generation(SHG) in square-law nonlinear crystalline material .

**Second harmonic generation** (**SHG**; also called **frequency doubling**) is a nonlinear optical process, in which photons interacting with a nonlinear material are effectively "combined" to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons. It is a special case of sum frequency generation.

Depending on the algorithm, two architectures for parallel-input digital multiplication can be considered, namely the DMAC (Digital Multiplication via Analogue Convolution) and the outer-product processors. These two cases need rather different post-processing arrangements for analogue-to-digital conversion of intermediate mixed-binary format results to a binary format. Schematic arrangements for the DMAC and outer-product processors are as follows:



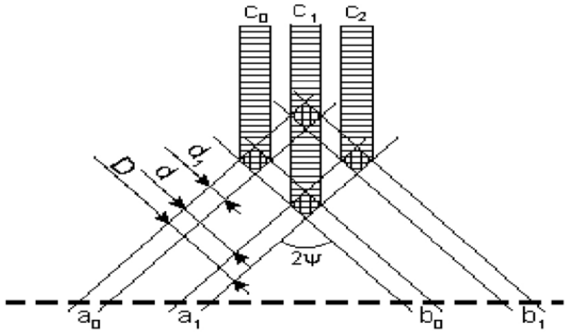


The figure show that the DMAC algorithm requires a smaller number, log2 (*N* + 1)-1, of adders and a smaller number, log2 log2 (*N* + 1), of summation steps, but the need for analogue-to-digital conversion limits the application of this algorithm. The outer-product algorithm requires a greater number, *N*-1, of parallel adders, achieving summation in a greater number, log2 *N*, of steps. However, in the alternative case there is no analogue-to-digital conversion, which seems to be preferable for the creation of all-optical components because it preserves the binary format and so removes a dynamic range problem.

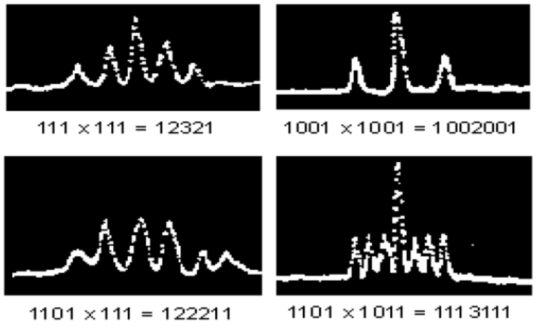
The full adder is the key component in all-optical post processing of intermediate results. Such an adder may be designed to use only the basic AND and EXCLUSIVE-OR logic gates, so implementation of a multiplier is conditioned by the feasibility of realizing high-speed all-optical logic gates. It is well-known that performing, for example, NOR and NAND logic operations as well as creating AND and NOT or NOT and OR logic gate pairs is sufficient for the arrangement of any arithmetic device, in particular for binary number multipliers. To achieve an extremely high speed of operation and ease of fabrication, it seems to be more promising first to obtain results in an intermediate mixed-binary format by a DMAC, or an outer-product processor, and then to convert that signal to a completely binary format.

The nonresonant Kerr effect is an ultrafast phenomenon that permits switching times as low as 10^-15 second, and makes possible an extremely high rate of logic operations in comparison with digital electronic signals. An application of ultrafast response requires an abnormally high intensity of light beams and the problem of heat removal becomes more complicated for the high density of information in the data flow. For this reason, the optical Kerr effect proves to be acceptable for computing first of all in low-loss optical fiber, because the heat power, given its small value, dissipates lengthwise along the optical fiber and does not lead to any difficulties even for the top speed of operation. However, the weak Kerr nonlinearity manifests itself only in a long length of fiber, so the output signal has a market time delay relative to the input signal. This time delay, nevertheless, should not be regarded as a considerable demerit for optical fiber components, because the data flow arrangement is such that performing each of the following operations does not depend on the results of all the previous processing operations.

At first, shaping the DMAC signal via a non-collinear SHG phenomenon in square-law optically nonlinear crystalline material is presented. The diagram of a non-collinear SHG phenomenon may be considered an all-optical AND logic gate. Such a gate has a femtosecond time response and does not need an optical pump beam, so that a widely branched network of coupled gates with repeated use of initial light beams may be implemented, because only a small part of the input signal energy is converted into the SHG output signals. In fact, each of the partial interactions corresponds to an undistributed field approximation. The light beam arrangement for the DMAC-algorithm signal shaping is shown as follows:



a.



111 × 111 = 12321

1001 × 1001 = 1002001

1101 × 111 = 122211

1101 × 1011 = 1113111

b.

Binary numbers are encoded by a total of *N* parallel optical channels, one channel for each of the *N* bits that comprise the following numbers:

$$A = \sum_{i=0}^{N-1} a_i 2^i \quad \text{and} \quad B = \sum_{i=0}^{N-1} b_i 2^i .$$

Intensities of light beams have magnitudes equal to 0 or 1 in both these channels. There are *N*2 areas of non-collinear interaction in a crystal when initial light beams pass through a crystal under a phase-matching condition. Similar areas play the parts of partial multipliers or AND logic gate networks, which are integrated into a single crystal. By providing an equidistant arrangement of the input optical channels, the intensities of the second-harmonic light beams are summed up along diagonal lines, so (2*N* + 1) parallel output channels prove to be shaped in the output plane. That is to say, the signals leaving the network arrangement are exactly the partial DMAC-signals:

$$c_i = \sum_{j=0}^{N-1} a_j b_{i-j}, \qquad C = AB = \sum_{i=0}^{2N-2} c_i 2^i.$$

In view of simultaneous arrival of optical pulses at each of the interaction areas, the initial optical beam fronts need to be sloped.

Both the intensity depletion of the initial signals as a result of repeated interaction in the convolution network and the diffraction of the optical beams have an effect on the number of bits, N, that can be handled in the processing of binary numbers. It may be shown that, on the one hand, for the processing of 32-bit numbers, the efficiency of the individual partial interactions ought to be no greater than 1% and, on the other hand side, the maximal value of bits *Nmax* is limited by diffraction to

$$N_{\max} = \sqrt{\frac{n_A D \ \sin 2\Psi}{8 \ \lambda_0}},$$

where lambda0 is the wavelength of the initial light beams, *nA* is the average refractive index for a crystal, and *D* is the geometric size. In the spatio-temporal soliton regime, this restriction can be omitted and the value *N* = 32 bits may be taken. The speed of operation is usually described by the time *T* for one operation performing as well as by the productivity *S*, *i.e.* the maximal number of bit operations in unit time:

$$T = \frac{2n_A D}{c \ \sin 2\Psi} + \tau, \qquad S = \frac{N^2}{\Delta T + \tau},$$

where *c* is the velocity of light, T is the bit pulse width, and delta*T* is the spreading time. The productivity *S* is defined by the maximum attainable frequency of data input into the operations, which is limited in its turn by the following factors:
a) the time response of the logic gates;
b) the bit pulse width;
c) the path time of one bit multiplication area; and
d) non-simultaneous responses of the logic gates in a convolution network.

## 4.2 Applications:

The preceding section outlined the structure and design issues of the DMAC/Outer product based Multiplier/Processor. This has a variety of applications including,

1. Design of Ultrafast All Optical digital systems
2. Ability to perform MAC (multiply and accumulate) which makes it possible to model all optical DSP's based on these algorithms.
3. The previous point implies that this could be used in a variety of signal processing applications like RADAR, Image/speech processing, Instrumentation, Biomedical applications etc..

## 5 Radio Over Fibre:

**Radio over Fiber** (RoF) refers to a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link to facilitate wireless access. Although radio transmission over fiber is used for multiple purposes, such as in cable television (CATV) networks and in satellite base stations, the term RoF is usually applied when this is done for wireless access .

In RoF systems, wireless signals are transported in optical form between a central station and a set of base stations before being radiated through the air. Each base station is adapted to communicate over a radio link with at least one user's mobile station located within the radio range of said base station.

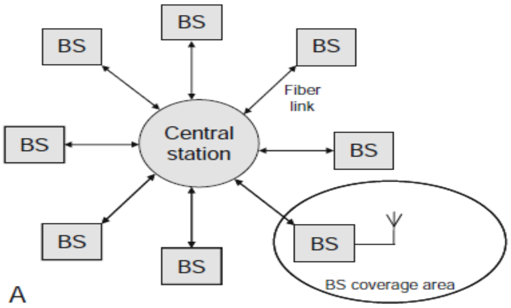
RoF transmission systems are usually classified into two main categories (*RF-over-Fiber* ; *IF-over-Fiber*) depending on the frequency range of the radio signal to be transported.

a) In **RF-over-Fiber** architecture, a data-carrying RF (Radio Frequency) signal with a high frequency (usually greater than 10 GHz) is imposed on a lightwave signal before being transported over the optical link. Therefore, wireless signals are optically distributed to base stations directly at high frequencies and converted to from optical to electrical domain at the base stations before being amplified and radiated by an antenna. As a result, no frequency up/down conversion is required at the various base station, thereby resulting in simple and rather cost-effective implementation is enabled at the base stations.

b) In **IF-over-Fiber** architecture, an IF (Intermediate Frequency) radio signal with a lower frequency (less than 10 GHz) is used for modulating light before being transported over the optical link. Therefore, wireless signals are transported at intermediate frequency over the optical.

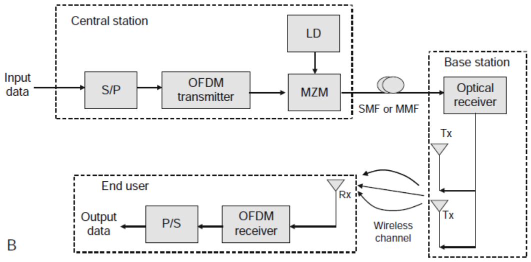
To reduce the deployment and maintenance cost of WiMAX and other wireless networks while providing low power consumption and large bandwidth, RoF technology is considered as a promising candidate. In RoF systems, the fiber is used to distribute the RF signal from a central station (CS) to remote antenna units. Different types of fibers, such as single-mode fibers (SMFs), multimode fibers (MMFs), and POFs, can be used. Possible applications include (1) in cellular systems to establish the connection between the mobile telephone switching office (MTSO) and base stations (BSs), (2) in WiMAX to extend the coverage and reliability by connecting WiMAX BSs and remote antenna units (RAUs), and (3) in UWB communications1 to extend the wireless coverage range. RoF can also be used to eliminate so-called dead zones (in tunnels, mountain areas, etc.), in hybrid fiber coaxial systems, and in fiber to the home applications. For example, to reduce system installation and maintenance costs for indoor applications, the POFs or MMFs can be used from residential gateway to either fixed or mobile wireless units inside a building. The RoF technologies offer many advantages with respect to wireless, such as low attenuation loss, large bandwidth, improved security, immunity to electromagnetic interference, reduced power consumption, and easy installation and maintenance.

One typical example of RoF systems is shown as follows:



A

The data for a given end user are generated in a CS, imposed on a set of OFDM subcarriers assigned to that particular user, transmitted over optical fiber upon modulation in a Mach–Zehnder modulator (MZM), and converted into electrical domain by the optical receiver in the BS. From the BS, the signal is transmitted over a wireless channel to the end user. An example of downlink transmission is shown as follows:



B

### 5.1 Photonic devices:

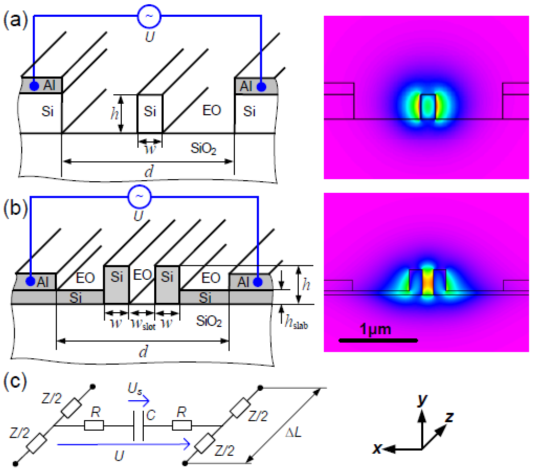
There are two major photonic devices used here. They are

1. Electro-Optical modulator, represented as MZM in the block diagram
2. Waveguide to fiber matching device

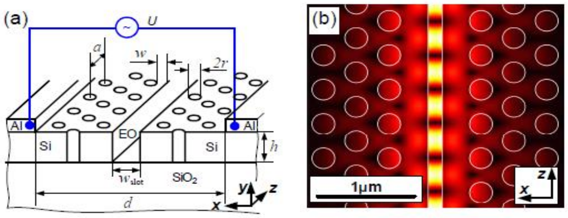
#### 5.1.1 Electro-optical modulator:

So far, the fastest modulation in silicon-on-insulator (SOI) waveguides was achieved by free-carrier injection. Modulation at 20 GHz in a silicon-based device was recently demonstrated with a reverse-biased pn-junction, allowing data transmission up to 30 Gbit . The size and power consumption of such devices can be considerably reduced by exploiting slow light in photonic crystal (PhC) waveguides .

The schematics for 3 Electro Optical modulator designs are shown below:



In the first model (a), the light is guided by silicon strips which are embedded in the electro-optic material (EO).The microwave field is applied via two aluminum conductor paths running in parallel to the optical strip waveguide. The spacing is chosen large enough (typically 1 micrometer) to avoid optical loss. For the slot waveguide (b) both silicon strips are doped and connected to the aluminum conductors by thin silicon slabs. (c) depicts a lumped element model of a short segment of the slot waveguide configuration. The optically isolating slab regions in (b) can be replaced by a photonic crystal (PhC) structure. This scheme is depicted below.



The optical intensity is high in the electro-optic material EO that fills the slot, see (b). As for the slab structure, the modulation frequency is limited by the RC time constant. The group velocity of the optical signal can be significantly reduced by an appropriate design of the PhC. The interaction time with the electro-optic material can thus be increased; this decreases the operating voltage and/or the device length.

### 5.1.2 Waveguide – Fiber Coupler:

For silicon waveguides above approximately 2μm in cross-sectional dimensions, some form of three-dimensional taper can be used but for smaller waveguides the loss is prohibitively large. The three-dimensional tapered waveguide transition can, in theory, offer a monolithically integrated means by which efficient coupling can be achieved.

The three dimensional taper is a gradual transition from a large cross-sectional waveguide area to a smaller one. Even for waveguides of several microns in cross-section, a taper can be advantageous, because it relaxes the alignment tolerances between the input fibre and the waveguide.

The aim is to produce a taper that reduces the waveguide dimensions in a smooth, lossless transition. The angle of the taper is typically very small to achieve the smooth transition, and it must also be produced with very low surface roughness. Lateral tapers are relatively straightforward to fabricate because this is essentially just an etching process from the top of the silicon wafer, but to produce a vertical taper requires a differential etch rate along the length of the taper.

Another taper structure is also available, and is called NVT mode-matching taper, which matches the fibre mode to the input mode of the taper structure. The large waveguide is then tapered to a point, transferring power to the underlying rib waveguide.

### 5.2 Advantages of RoF:

**Low Attenuation**

It is a well known fact that signals transmitted on optical fiber attenuate much less that other medium, especially when compared to wireless medium. By using optical fiber, the signal will travel further reducing the need of repeaters.

**Low Complexity**

RoF makes use of the concept of a Remote Station (RS). This station only consists an optical-to-electrical (O/E) ( and an optional frequency up or down converter), amplifiers, and the antenna. This means that the resource management and signal generation circuitry of the Base Station can be moved to a centralized location and shared between several remote stations, thus simplifying the architecture.

**Lower Cost**

Simpler structure of remote base station means lower cost of infrastructure, lower power consumption by devices and simpler maintenance all contributed to lowering the overall installation and maintenance cost. Further reduction can also be made by use of low cost Graded Index Polymer Optical Fiber (GIPOF)

**Future Proof**

Fiber Optics are designed to handle gigabits speeds which means they will be able to handle speeds offered by future generations of networks for years to come. RoF technology is also protocol and bit-rate transparent, hence, can be employed to use any current and future technologies.

### 5.3 Applications of RoF:

**Access to dead zones**

An important application of RoF is its use to provide wireless coverage in the area where wireless backhaul link is not possible. These zones can be areas inside a structure such as a tunnel, areas behind buildings, Mountainous places or secluded areas such a jungle.

**FTTA (Fiber to the Antenna)**

By using an optical connection directly to the antenna, the equipment vendor can gain several advantages like low line losses, immunity to lightening strikes/electric discharges and reduced complexity of base station by attaching light weight Optical-to-Electrical (O/E) converter directly to antenna.

## 6 Conclusion:

Thus fundamental concepts regarding silicon photonics and photonic crystals were outlined, and then design issues and applications for a photonic based Mobile Communication system(RoF) and an all optical multiplier based on Second Harmonic Generation were elaborately presented. These techniques would be potential contenders in revolutionizing the world of Telecommunication and signal processing, effectively replacing electronics with photonics, which would result in extremely fast devices and reduced thermal effects.

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