Progress in high index contrast integrated optics

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Abstract: *A large fraction of the recent innovation in integrated optics is enabled by the use of high index contrast structures and devices. The strong confinement achievable in such devices allows for dramatic performance benefits and downscaling. In this paper the progress in this field is reviewed.*

Introduction

Photonic components with a high refractive index contrast in their device structure have gained strong interest over the past decade. High index contrast does not have a strict definition but roughly speaking the ratio of the difference between the highest and the lowest refractive index in a device to their sum should be of the order of 50% or more before one can truly exploit the benefits of this high contrast. This ratio is a measure for the field reflectivity of the high contrast interface under normal illumination. More precisely the absolute value of this ratio should be of the order of 50% or more. With this definition one can include media with complex refractive index, such as metals, and hence plasmonic devices also belong to the class of high index contrast devices.

High index contrast allows for strong confinement and ultra-compact devices. Strong confinement is important both for linear and non-linear devices. In linear devices it allows to control the propagation of light from a small volume of material. This is important in sensors as well as in low-power and /or high speed active components. In non-linear devices strong confinement allows to achieve all-optical functions at moderate power levels. The strong confinement can be achieved either by waveguide confinement or by cavity confinement or by a combination of both. In case of cavity confinement high index contrast allows to realize small cavities with high quality factor. This implies that one can realize very selective filters with a high free spectral range, which is important in many applications. In particular photonic crystal devices have led to spectacular progress in this field.

High index contrast also allows to realize compact beam or mode conversion devices both for situations with and without change of direction. In-plane bends can be very compact and the same holds for out-of-plane couplers. High index contrast allows to implement very short adiabatic tapers and even shorter non-adiabatic mode conversion devices.

In this paper a number of developments in high index contrast devices will be reviewed. First the major material systems for high index contrast devices will be described. Then the progress in waveguide confinement, mode conversion and cavity confinement will be described. Finally we describe some of the challenges this research field faces.

Materials

High index contrast can most easily be achieved by using a combination of a semiconductor material with a low-index dielectric or by a combination of a metal with a semiconductor or a dielectric.

The most popular material system for high index contrast devices is definitely the silicon-on-insulator (SOI) system. High quality 200 and even 300 mm SOI-wafers are manufactured industrially today. For photonic purposes these wafers typically consist of a crystalline silicon layer with a thickness of a few 100 nm on a buffer layer of silica of a few micrometer on a silicon substrate. Alternatively one can use polycrystalline or amorphous silicon layers, which provides a great flexibility in the underlying substrate. The fact that SOI photonic devices can often be manufactured by means of CMOS-oriented technologies is a major driver for this material choice [1-2].

Next in importance is the use of high index III-V semiconductor layers in combination with dielectrics. The fabrication of thin III-V layers on a dielectric involves the use of a bonding step between the III-V substrate and the host substrate, followed by substrate removal of the III-V substrate. In recent years there has been considerable progress in the development of wafer-to-wafer and die-to-wafer bonding methods, either by exploiting molecular bonding [3] or by using adhesive bonding, for example by using BCB as bonding agent [4].

An important development in this context is the combination of a III-V high index contrast layer above an SOI high index contrast layer. This allows for the integration of III-V active devices (lasers, detectors...) with passive SOI waveguides [5-7].
In the specific case of the GaAs/AlGaAs system the bonding step can be avoided by oxidising a high Al-content AlGaAs-layer beneath a GaAs-layer. While this is an elegant approach, technologically speaking, the range of device functionalities it offers is relatively limited.
Plasmonic devices are typically based on modes propagating at the interface of noble metals and dielectrics or semiconductors. In terms of layer structure these devices are very simple to make. However they always suffer from losses due to the metal absorption. Therefore to make practical use of plasmonic devices it will generally be necessary to combine (compact) plasmonic device structures with waveguide structures based on dielectrics and semiconductors.

Waveguide confinement

In a waveguide structure the propagating mode can be confined to a very small cross-section when high index contrast is exploited. In a simple stripe waveguide with real refractive index the mode can be confined to an area of the order of a square wavelength. In a plasmonic structure the field can be confined further to sub-wavelength dimensions. The same holds for slotted real-index waveguides where the low index slot can have a very high confinement factor.
The strong confinement is not only important for passive functions such as bends, as described below, but also to optimize the efficiency or sensitivity of certain functions. In the case of active functions – functions whereby the mode propagation is influenced somehow by something over time – it can be of key importance that the active part of the structure is as small as possible. This allows to make active devices power efficient and/or fast and it allows to make sensors - that sense the presence of an adlayer - sensitive.
As an illustration the potential of various high index contrast SOI waveguide structures for sensing applications is shown. In Fig. 1 we have plotted the change in effective index of the guided modes as a function of the thickness of a thin adsorbed layer (n=1.45) at the waveguide surface ($\partial n_{eff} / \partial t_{adlayer}$ [1/µm]). By using different transduction principles (interference, resonance, mode coupling) the effective index of the guided modes can be read out as a power difference, thus enabling sensing action. Comparison between three different waveguide geometries, the surface plasmon interferometer geometry on SOI [8] with an adsorbed layer on top, a single mode SOI waveguide (220 nm thick, 450 nm broad) with an adsorbed layer on top and a slotted waveguide (same single mode waveguide but with a slot of 50 nm and the adsorbed layer on the slot walls) show the enormous potential of the TE mode of slotted waveguides for sensing applications.

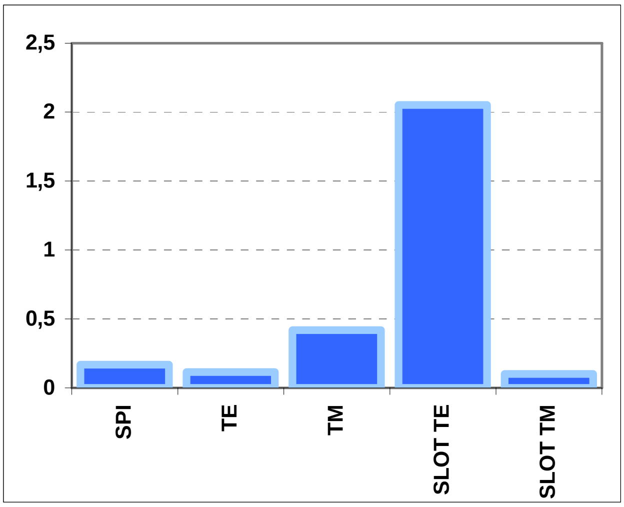

Figure 1: Comparison of different waveguide geometries for sensing applications. $\partial n_{eff} / \partial d_{thickness}$ [1/µm] for surface plasmon modes (SPI), single modes SOI waveguides (TE and TM) and slotted single mode SOI waveguide (SLOT TE and SLOT TM)

Mode conversion

Mode conversion – both in terms of mode size and mode propagation direction - is important in guided wave optical systems.
The most obvious example is given by bends, which are ubiquitous in integrated optical circuits. High index contrast allows to make very sharp bends with radii of curvature down to the scale of the wavelength [9-10]. Bend losses were measured using spiral waveguides with up to 600 bends, allowing for an accurate fit. As expected, bend losses increase for smaller radii, but we can see that even for a 2µm bend radius the excess bend loss is manageable for a small number of bends per circuit. For more extensive circuits with many bends, a radius of at least 3µm is recommended.

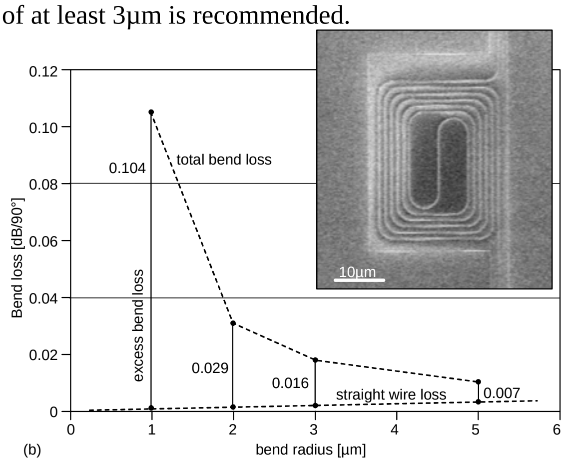

Figure 2: Bend losses for various bend radii measured through spiral waveguides

The next important example is given by fiber coupling between a photonic chip and an optical fiber. The tight confinement in high index contrast waveguides was often seen as a disadvantage given the difficulty to couple light efficiently to low index contrast optical fibers. However it has turned out to be relatively easy to convert a mode tightly confined in a high index contrast waveguide into a fiber matched mode and to do so on-chip, thereby alleviating the alignment tolerances of the packaging process.

In a first approach, the waveguide is adiabatically tapered down until the guide no longer confines the optical field and the light is pushed upwards to a polymer or SiN overlay. This approach has been demonstrated by several groups [1, 11-12], with coupling losses below 1dB, has a large bandwidth and does not require complicated processing. However, this approach does not allow for wafer testing, it requires the definition of very narrow silicon lines (<80nm) and in most cases the overlaying waveguide is coupled to a lensed fibre or a high numerical aperture fibre, which results in smaller alignment tolerances.

In a second approach, a diffraction grating is used to couple light between the planar waveguides and an out-of-plane butt-coupled standard fiber. Thanks to the high refractive index contrast, the grating can have a short coupling length. A typical SOI grating coupler consists of roughly 20 grating periods and consequently has a relatively large bandwidth. A basic grating coupler on a standard SOI wafer with an experimental coupling efficiency > 30% and a 1dB bandwidth of 40nm was presented in [13]. An advantage of the grating coupler approach is that standard single mode fibers are used and consequently the alignment tolerances are more relaxed. The efficiency can be improved by using more advanced designs and custom layer stacks. Using a silicon overlay layer, the efficiency can be increased to 78% theoretically.[14] An efficiency of 70% was demonstrated in [15] by adding a gold bottom mirror using wafer bonding technology.

Cavity confinement

Cavity mode volume and cavity Q-factor are the key parameters that determine the performance of cavity-based devices. High index contrast allows to reduce the cavity mode volume while keeping the Q-factor high. This is important for low power and/or high speed operation of microlasers, tunable filters, modulators, switches and all-optical nonlinear functions. It is also important for adlayer sensing devices in that it makes these devices sensitive to very small volumes of the adlayer material.

The two most prominent types of cavities, based on high index contrast, are the microring (or disk) resonator and the photonic crystal cavity.

Several high-Q ring resonators were demonstrated. For optical channel drop filters, the transmission should be maximized. The internal losses limit the Q due to trade-off between external coupling and transmission. Ring resonators based channel drop filters with 5µm radius have been demonstrated with Q values in the range of 5 000 - 20 000 [10, 16]. These resonators have single-mode waveguides with an effective mode area of around $0.25µm^2$. For applications such as sensors, obtaining a high Q is more important, and external coupling can be decreased. With current fabrication technology, waveguide losses are low enough to increase the ring circumference, which decreases the free spectral range and in this way further decreases the 3dB bandwidth and increases the Q factor. Q factors as high as 45000 to 139000 were shown with ring resonators with a radius of 20-30µm, coupled to a single waveguide [17-18]. However, useful Q factors for sensing can already be obtained with much smaller rings with 3-5µm radius.

As far as photonic crystal cavities are concerned, two routes to achieve high Q are popular. One design is based on point defects where the local neighbourhood is deformed in such a way as to minimise leaking Fourier components [19] or create a gentle Gaussian-like field profile [20]. In that last publication, Q-factors of 100 000 were experimentally observed in an SOI material system with a model volume of 0.7 cubic wavelengths.

Even higher performance can be achieved by a design based on locally perturbed line effects. By modulating a line defect, Notomi experimentally showed a Q-factor of 800 000 with a volume of 1.4 cubic wavelengths [21]. Noda proposed a double heterostructure design, also in SOI, which led to observed Q-factors over almost one milion, still with very small modal volumes of 1.2 cubic wavelengths [20].

The Q-factors which are currently achieved in active materials like InP by e.g. the Caltech group are lower than their SOI counterparts, but still reach a respectable 13 000 in laser cavities [22].

Challenges

While the potential of high index contrast devices is large, the challenges are also very large.

At the conceptual level, one of the major challenges is polarisation independence. For devices with input light coming from an optical fiber, the behaviour should preferably be polarisation independent. Theoretically speaking it may be possible to design waveguides and cavities with a polarisation independent behaviour but this leads to a very drastic reduction of the design freedom in relationship to other performance aspects and it will be extremely challenging from a technological point of view. Therefore the better option may be to make sure that the application is not critically dependent on polarisation independence or to make use of polarisation diversity approaches. The fiber grating couplers described earlier can be extended to polarisation splitting functionality and thereby offers an elegant solution for polarisation diversity. This has been demonstrated for the case of wavelength demultiplexers [23].

A second challenge relates to design and modelling. In low index contrast photonic devices, one is used to a situation where a collection of theoretical models and approximations in conjunction with a range of CAD tools allows to design these devices accurately and efficiently. In high index contrast devices on the contrary, it is often necessary to make use of rigorous vectorial simulation methods in three dimensions. This often means that the computing times are very large and/or the accuracy is low. What makes things worse is the fact that it is much more difficult to use intuition as part of the design process when dealing with high index contrast.

The major challenges of high index contrast photonics have to do with technology however. The geometrical accuracy of high index contrast structures needs to be extremely good. The dimensions of the smallest features – with dimensions of a few 100 nm or even less – should typically be correct down to the 1-10 nm range. An error of 10 nm on a critical wavelength scale dimension (waveguide width or thickness, cavity length...) will typically lead to a shift of the order of 10 nm in the spectral behaviour of the component. Short range geometry deviations – roughness – should also be extremely small. Roughness is still considered to be the major cause of loss mechanisms in most high index contrast devices.

A further technological (and conceptual) challenge is presented by active devices involving a pn-junction. Given the compactness of high index contrast devices, it is far from trivial to design (and fabricate) these devices in such a way that the current flow is used effectively while the doped areas do not lead to loss penalties. Something similar holds for the problem of heat removal, especially since most high index contrast devices involve bonding layers with a low heat conduction capability.

A final challenge is present in the transition from research to industrial deployment. With the technology issues in high index contrast photonic components being so demanding, it is unlikely that many companies can afford to own their own fab. This is definitely true at the prototyping level and as long as the market size is modest. Even for many research groups it will become increasingly difficult to have all technological tools in house. Therefore there is a need for an approach whereby research, prototyping and small volume production is possible in an open access fab, which can serve many actors. For the case of silicon-on-insulator, such an open access structure is already operational in the form of a silicon photonics technology platform [24]. This is possible because (and *only* because) silicon photonics can rely on an existing CMOS-technology base. The fact that the CMOS world is at present trying to diversify with a “More than Moore” vision may well offer a unique win-win opportunity.

This platform, set up in the framework of the European network of excellence ePIXnet, provides a facility access service in which users can have designs fabricated in the form of a multi-project wafer run, where as many contributions as possible are grouped together to bring down the cost to a level acceptable for research groups. Actual fabrication is handled in an advanced CMOS research facility [2, 24].

Conclusion

High index contrast photonic components and integrated circuits have a great potential but do also present important challenges. However in the past 5-10 years there has been an enormous progress in this field at the level of proof-of-principle devices. It is realistic to expect that the next 10 years will bring deployment in the form of products with unique performance and/or lower cost as compared to their lower index contrast counterparts. To what extent this will happen will strongly depend on the way the research and industrial photonics community organizes itself. A foundry-oriented model will be a key ingredient and may well make the difference between niche and large volume deployment.

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