32nd URSI GASS, Montreal, 19-26 August 2017

Photonic Skin-Depth Engineering for Transparent Sub-diffraction Photonics

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Abstract

The miniaturization of optical devices with low power consumption on CMOS platforms can pave the way for densely integrated photonic circuits. A major roadblock in this process is the large skin depth of evanescent light waves generated in nanoscale light confinement. In this paper, we demonstrate the roll of multilayer anisotropic all-dielectric metamaterials in the control of evanescent waves. This fundamentally new approach uses optical waveguides with an average index higher in the cladding compared to that of the core. It marks a completely different approach of light confinement compared to photonic crystal and slot waveguides. These devices are a scalable process and can be implemented on a CMOS platform which will lead to a large impact on future devices designs in photonic integrated circuits.

1. Introduction

The integration of nanoscale electronics with conventional optical devices is restricted by the diffraction limit of light. Metals can confine light at the subwavelength scales needed and they are lossy, while dielectric materials do not confine evanescent waves outside a waveguide or resonator, leading to cross talk between components. We show that light can be confined below the diffraction limit using completely transparent artificial media (metamaterials with $\varepsilon>1, \mu=1$). Our approach relies on controlling the optical momentum of evanescent waves—an important electromagnetic property overlooked in photonic devices. For practical applications, we propose a class of waveguides using this approach that outperforms the cross-talk performance by 1 order of magnitude as compared to any existing photonic structure. Our work overcomes a critical stumbling block for nanophotonics by completely averting the use of metals and can impact electromagnetic devices from the visible to microwave frequency ranges.

Total internal reflection (TIR) is a ubiquitous phenomenon used in photonic devices ranging from waveguides and resonators to lasers and optical sensors. Controlling this phenomenon and light confinement are keys to the future integration of nanoelectronics and nanophotonics on the same silicon platform. We introduced the concept of relaxed TIR, in 2014, to control evanescent waves generated during TIR. These unchecked evanescent waves are the fundamental reason photonic devices are inevitably diffraction limited and cannot be miniaturized. Our key design concept is the engineered anisotropy of the medium into which the evanescent wave extends. We show how our work can overcome a long-standing issue in photonics, namely, nanoscale light confinement with fully transparent dielectric media.

2. Relaxed Total Internal Reflection

In conventional TIR, if $n_1 > n_2$ and the incident angle is greater than the critical angle ($\theta_c = \sin{-1}\,(n_2/n_1)$), light is reflected back to the first medium and decays evanescently in the second medium (Fig 1a). However, we have recently demonstrated that the conditions for TIR at an interface between an isotropic and anisotropic dielectric are relaxed to:

$$n_1 > \sqrt{\varepsilon_{2x}}, \qquad \text{p polarization (1a)}$$

$$n_1 > \sqrt{\varepsilon_{2y}}, \qquad \text{s polarization (1b)}$$

where [ε_{2x} ε_{2y} ε_{2z}] is the permittivity tensor of the second anisotropic medium and the interface between the two media lies on the yz-plane (Fig. 1b). As a result, the critical angles for p and s polarized light become:

$$\theta_c = sin^{-1}\left(\sqrt{\varepsilon_{2x}}/n_1\right) \qquad \text{p polarization (2a)}$$

$$\theta_c = sin^{-1}\left(\sqrt{\varepsilon_{2y}}/n_1\right) \qquad \text{s polarization (2b)}$$

These relaxed conditions imply that we can arbitrarily increase or decrease the permittivity of the anisotropic material in the z direction, while still preserving TIR. This additional degree of freedom can thus be used to control the skin depth of evanescent waves. If $\varepsilon_{2z} >> 1$, evanescent waves decay faster than in vacuum allowing for strong confinement inside the core of a dielectric waveguide. We note that in this limit, the averaged index in the anisotropic medium 2 can be larger than that of the isotropic medium 1 while still totally reflecting light above the critical angle.

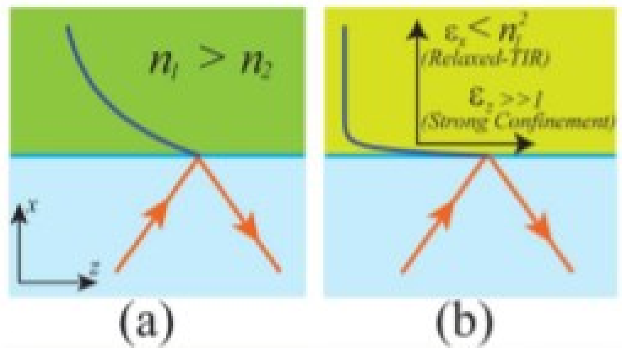

Figure 1. (a) Conventional TIR where if $n_1 > n_2$ and the incident angle is larger than the critical angle, light is totally internally reflected to medium 1 and decays evanescently in medium 2. (b) Relaxed TIR where if $n_1 > \sqrt{\varepsilon_{2x}}$ and the incident angle is larger than critical angle, light is totally reflected into medium. The skin-depth can be considerably reduced if $\varepsilon_z >> 1$.

3. Controlling Optical Momentum

In conventional TIR, evanescent waves have a large skin depth and penetrate far into the second medium. Here we demonstrate how to control momentum of evanescent waves. From the dispersion relation for an anisotropic medium, we find that for TM polarized waves:

$$k_x^{\perp} = \sqrt{\frac{\varepsilon_z}{\varepsilon_x}} \sqrt{\varepsilon_x (k_o)^2 - (k_z^{||})^2} \qquad (3)$$

Thus, the skin depth is governed by the ratio of permittivity components in the anisotropic medium. We thus arrive at the condition that $\varepsilon_z >> 1$ to increase the momentum and decrease the skin depth of evanescent waves. Since the condition for relaxed TIR and momentum confinement are decoupled, we can simultaneously achieve both. This is a fundamentally new approach in light confinement.

Our non-resonant transparent medium alters light momentum that enters it. The upper limit on momentum parallel to the interface is set by the permittivity perpendicular to the interface, while the perpendicular momentum is increased by the dielectric constant parallel to the interface. For plane wave propagation along the symmetry axis of anisotropic media, the field direction and permittivity tensor component are orthogonal to the wave vector. This is a brand new approach to light confinement that is non-intuitive.

4. 1D Practical Realization

No naturally occurring medium has strong enough anisotropy to meet the requirements presented above. The maximum contrast between dielectric constant components is highest for TiO_2 or in artificial polymers. However, this is still quite low so we must use artificial media.

Our practical approach consists of a periodic multilayer structure consisting of two materials with high index contrast and layer thicknesses much smaller than the telecommunication wavelength of light used here. The materials chosen are silicon and silicon dioxide as they are abundant and CMOS compatible. Effective medium theory for this structure predicts a homogenized medium with anisotropic dielectric constant values given by:

$$\varepsilon_{||} = \varepsilon_{Si}\rho + \varepsilon_{SiO2}(1-\rho) \qquad (4a)$$

$$1/\varepsilon_{\perp} = \rho/\varepsilon_{Si} + (1-\rho)\varepsilon_{SiO2} \qquad (4b)$$

where $\varepsilon_{\perp}$ and $\varepsilon_{||}$ are the dielectric constants perpendicular and parallel to the interface and ρ is the filling fraction of silicon. A schematic of a one dimensional e-skid waveguide is shown in Figure 2a. The blue region is the waveguide core and the grey regions are the anisotropic metamaterial cladding.

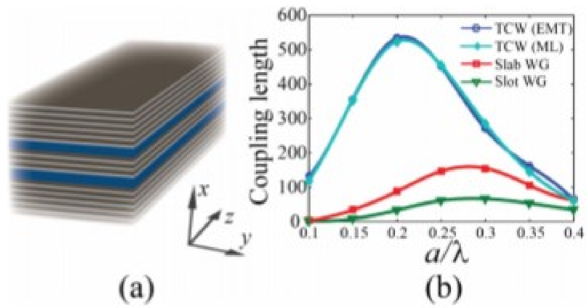

Figure 2. (a) Anisotropic metamaterial cladding (grey) surrounding a silicon core (blue) in a 1D practical realization of our light confinement approach. Multiple waveguides can be placed adjacent to each other in photonic integrated circuits. (b) Comparison of coupling length (cross talk) for conventional slab waveguides, slot waveguides, and the e-skid waveguide. The e-skid waveguide improved the coupling length by one order of magnitude and the mutilayer structure result is consistent with the anisotropic EMT material cladding. The slot size is 0.01λ for each waeguide and the center to center seperation is 0.5λ.

The major advantage of our approach for practical applications is the reduction of the cross talk once the multilayer anisotropic cladding is introduced in the region between two conventional waveguides. This is because our approach decreases the skin depth of evanescent waves in the cladding of the waveguide, which is the origin of cross talk. We consider two silicon slab waveguides and place them next to each other with center to center separation of 0.5λ. The dielectric constants of the multilayer structure are close to silicon and silicon dioxide at the telecommunication wavelength with a silicon filling fraction of ρ = 0.6. Figure 2b shows the coupling length calculated for two waveguides with the multilayer cladding and with a silica cladding. There is a one order of magnitude increase in the coupling length. A slot waveguide is also calculated for comparison, but it does not perform as well as our metamaterial cladding.

5. Better than Vacuum?

It is commonly believed that, to confine light inside the dielectric waveguides, we should increase the contrast between the indices of the core and the surrounding medium or cladding. At the telecommunication wavelength (1550 nm) silicon has the highest refractive index among lossless dielectric. Thus it is logical that the silicon waveguide surrounded by vacuum will have the strongest power confinement inside the core (Fig 3a). However, if we surround the core with a transparent anisotropic dielectric as demonstrated in Figure 3b, the waveguide can confine the fundamental HE mode better than the silicon-vacuum approach. To satisfy the relaxed TIR condition, the index contrast must be as large as possible with $\varepsilon_x < \varepsilon_{Si}$ and $\varepsilon_z = \varepsilon_{Si}$. In Fig. 3c and 3d, the x component of the electric field is compared in each waveguide. It is seen that the anisotropic metamaterial cladding outperforms vacuum by a factor of 15 by confining 30% of the power in the core compared to only 2% with the vacuum cladding. The radius of the core is the same in both cases with r = 0.07λ to allow propagation of sub-diffraction limit information.

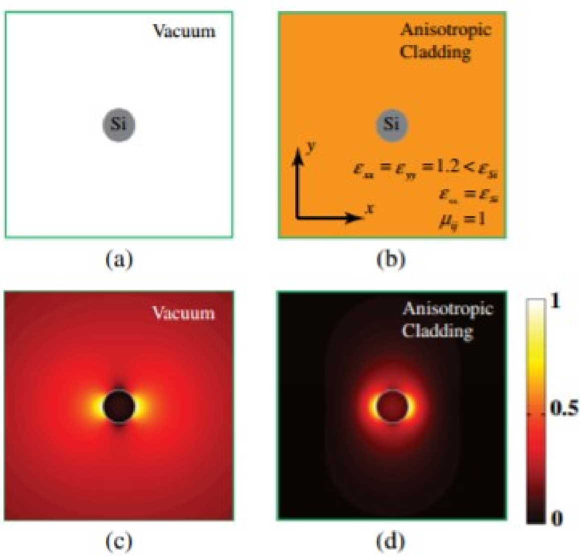

Figure 3. (a) It is well known that the best waveguide for low-loss power confinement is a silicon core surrounded by a vacuum cladding. (b) We prove that a silicon waveguide surrounded by anisotropic cladding, can strongly increase the light confinement inside the core. (c) The x-component of the electric field of fundamental HE_{11} mode where 2% of the power is confined in the core. The core radius is r = 0.07λ to allow sub-diffraction confinement. (d) The x-component of the electric field with anisotropic cladding where 30% of the power is confined in the core.

6. Comparison with Other Approaches

The search for the replacement of optical fibers in photonic integrated circuits has led to the design of many waveguide structures. These waveguides can be either metallic (plasmonic) or dielectric. Metallic waveguides are mostly used at microwave frequencies due to their high reflectivity. However, designs using surface plasmon polaritons at optical frequencies have been proposed. These are useful for sensing, but not sub-diffraction confinement as plasmons have a short propagation length. Recently, the hybrid plasmonic waveguide (Fig. 4a) has been proposed that confines light in a low index gap above metals, reducing the field penetration in the metal which increases the propagation length of the plasmon.

Dielectric slot waveguides (Fig. 4b) and photonic crystal waveguides (Fig. 4c) are the two major dielectric structures which are able to strongly confine light. The field intensity goes up in a tiny low index gap surrounded by two high index rods in slot waveguides which allows for sub-diffraction confinement. Photonic crystal waveguides can contain and confine light in defects in the engineered photonic band gap, as long as there is no disorder. However, when both of these structures are fabricated close together, light can easily be coupled into adjacent waveguides, resulting in considerable cross talk. Our extreme skin depth (e-skid) waveguide (Fig. 4d) has shown to drastically reduce cross talk between adjacent waveguides while allowing confinement of sub-diffraction modes in the waveguide.

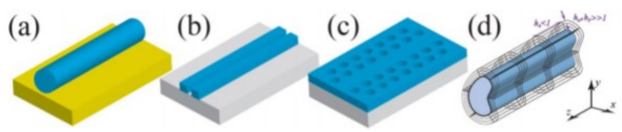

Figure 4. (a) Schematic of a hybrid plasmonic waveguide. (b) Dielectric slot waveguide. (c) Photonic crystal waveguide. (d) Extreme skin depth (e-skid) waveguide.

7. Summary

In summary, we have introduced a photonic platform implemented on the CMOS foundry with a unique functionality of controlling evanescent waves on-chip. We have shown that high index periodic multilayer metamaterials in the deep sub-wavelength limit can act as an all-dielectric metamaterial cladding for simultaneously achieving TIR and controlling the skin-depth of evanescent waves. The cross-talk is reduced by an order of magnitude between adjacent waveguides. This work paves way for all-dielectric metamaterials to become practical and be integrated into CMOS photonics to achieve improved integrated circuits.

8. Acknowledgements

I would like to acknowledge my research group members Saman Jahani, Farid Kalhor, Ward Newman, and Prashant Shekhar for their contributions to this work. I would also like to acknowledge Prof. Ray Decory and Prof Vien Van for allowing the use of their lab equipment in contributions to this work.

9. References

1. S. Jahani and Z. Jacob, "All-dielectric metamaterials", *Nature Nanotechnology,* Vol. 11, pg. 23-26, 2016.

2. S. Jahani and Z. Jacob. Photonic skin-depth engineering. *Journal of the Optical Society of America B*, Vol. 32 pp.1346-1353, 2015.

3. S. Jahani and Z. Jacob. Transparent sub-diffraction optics: nanoscale light confinement without metal. *Optica*, Vo. 1(2), August 2014.

4. S. Jahani and Z. Jacob. Breakthroughs in photonics 2014: Relaxed total internal reflection. *Photonics Journal IEEE*, Vol. 7(3), 2014.