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# Novel structures for high confinement in sub-wavelength regions

Michal Lipson, Jacob T. Robinson,Qianfan Xu, Vilson Almeida
Department of Electrical and Computer Engineering, Cornell University, Ithaca NY 14853

Hod Lipson
Departments of Mechanical & Aerospace Engineering and Computing & Information Science, Cornell University, Ithaca NY 14853

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**Abstract**

We show high confinement in novel index nm-size waveguides and cavities. Enhancement of light by a few orders of magnitude relative to the input light is observed.

## Introduction

Confinement of light to small regions has important applications in the development of low threshold lasers as well as increasing local intensity dependent non-linear effects for optical sensing switching, modulation.[1] . Cavities and high confinement waveguides have been shown using either high index media[1,] or photonic crystals[2], leading to confinement in volumes of the order of the wavelength in the material. Here we show high confinement in one and two dimensional novel structures of sub-wavelength dimensions. In contrast to the mechanism of interference in periodic media used in photonic crystal waveguides and cavities, the mechanisms of confinement of the structures shown here are based on strong field discontinuities, and on scattering in pseudo-random media.

## High confinement in sub-wavelength waveguides

The waveguiding structure studied here, called slot-waveguide, consists of a dielectric nanometer-wide low-index ($n_S$) slot embedded between two rectangular high-index ($n_H$) regions, both surrounded by a low-index ($n_C$) cladding. The principle of operation is based on the discontinuity of the normal component of the electric field at the high-index-contrast interface;[3] the major component of the electric field of the quasi-TE mode ($E_x$) is perpendicular to the walls of the slot, thereby undergoing strong discontinuity at the walls, with much higher amplitude in the low-index slot (see Fig. 1). The ratio between $E_x$'s at both sides of the walls equal to the square of the index-ratio across the wall ($n_H^2/n_S^2$), which equals to 12 for an air slot embedded between two silicon regions. When the dimension of the slot is smaller than the decay length of the field from the interface into the low index region, the electric field remains high within the slot. The magnetic field is continuous at the walls of the slot; therefore, the optical intensity in the slot is much higher than that in the high-index region. The power transmitted in a sub-100-nm-wide low-index slot can be higher than 40% of the total power when the slot-waveguide is optimally designed. Note that in contrast to the leaky modes used in photonic crystals, the guiding mode is an eigenmode of the proposed structure and is therefore fundamentally lossless with very low wavelength sensitivity.

We have fabricated the structure and shown[4] that the field is indeed confined mainly in the low index media. simulated the eigenmodes of the fabricated structure using a full-vectorial finite difference mode solver[5] with a non-uniform grid mesh, taking the refractive index in the slot as $n_S$ = 1. The simulated transverse electric field distribution of the quasi-TE mode is shown in Fig. 2. In the figure, one can clearly see the field discontinuities at index-contrast interfaces and the strong field confinement in the slot.

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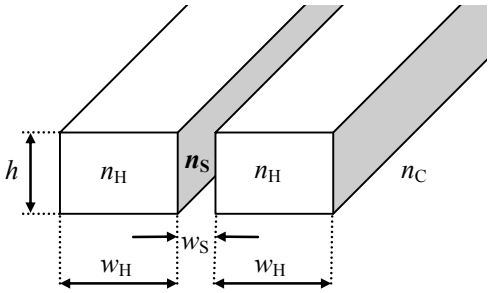



Fig. 1. Schematic of the slot-waveguide

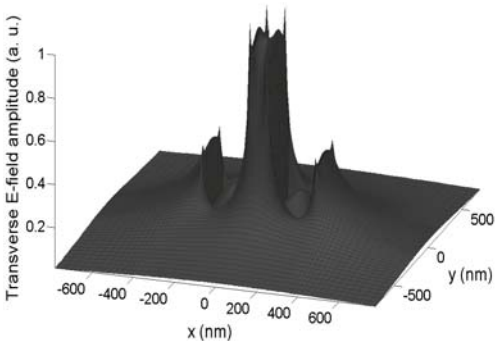



Fig. 2. Transverse electric field of the quasi-TE mode in a silicon-on-insulator-based slot-waveguide.

## High confinement in sub-wavelength cavities

*Confinement in slot regions*

Using the principle of confinement described above for waveguides, a strong confinement in cavities can be achieved, in low index regions with nm-size dimensions. Figure 3 shows a cavity based on the slot waveguide together with the TM field distribution in the structure. The diameter of the central Silicon disk is 350nm, and the width of the air slot and the outside silicon cladding are 20nm and 95nm, respectively. The 20nm slot is embedded in a Silicon disk. Note that contrary to standard disk resonators the diameter of the cavity is only 540nm

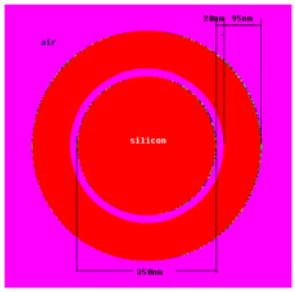



Figure 3a: Structure of the micro-slot-ring of silicon in air. The diameter of the central disk is 350nm, and the width of the air slot and the outside silicon cladding are 20nm and 95nm, respectively.

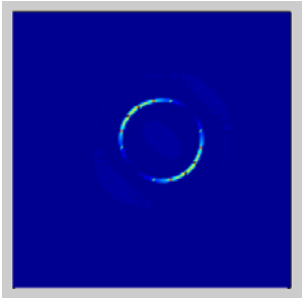


Figure 3b: The field intensity distribution of the TM mode of the micro-slot-ring. The maximal intensity inside the air slot is about 18 times larger than that outside of the slot.

*Confinement in pseudorandom structures*

Microdisk and ring resonators, as well as photonic crystal cavities, as well as the ones shown in Fig. 3 have well defined geometries in which the confinement of light occurs in a $m\lambda/2n$ cavity (where m is an integer and n is the effective index of refraction of the cavity medium). Here we present a new method of light confinement using a pseudo-random arrangement of sub-wavelength high-index scattering media. The dielectric structure studied here is shown in Fig. 4a. It consists of an input slab waveguide operating at 1549.5 nm with a TE polarization (E points out of the plane) incident on a 5.04 $\mu$m by 5.28 $\mu$m grid. The grid is composed of 120 nm by 120 nm squares which are either a high ( $n_H = 3.50$ ) or low index ( $n_L = 1.46$ )dielectric material.. In the 2D FDTD computation these squares represent infinitely long rods which extend into and out of the plane. Notice that contrary previous work in aperiodic structures [5], there are no apparent

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long or short range order parameters. It is important to note also the configuration of the structure near the end of the input waveguide at $x = 0\,\mu\text{m}$, $y = 0\,\mu\text{m}$ (see Fig. 4(b)). The intensity enhancement (calculated from the FDTD simulation) superimposed over the structure in Fig. 1(a) shows a peak average intensity os over 200 times that of the input waveguide. The effective modal area is $0.0465 \pm 0.0015\,\mu\text{m}^2$.

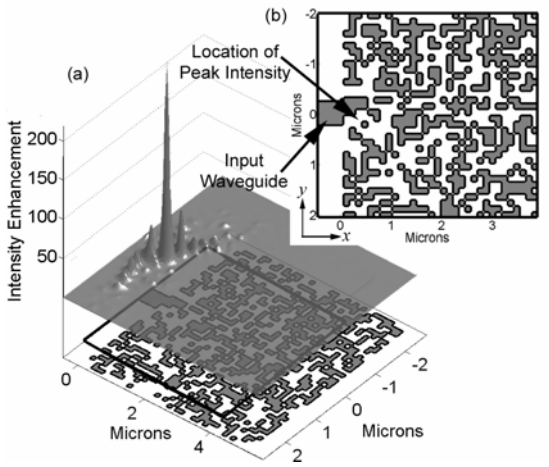



Fig. 4. (a) 2D FDTD simulation of the time-averaged intensity normalized to the input intensity in the optimized pseudo-random dielectric structure (b) top view of the boxed portion of the dielectric structure.

The structure shown in Fig. 4 was designed using evolutionary algorthims (EAs). Inspired by natural evolution, EAs operate by repeatedly selecting, varying, and replicating successful individuals in a population of candidate solutions. Such algorithms have successfully been applied to the design of a number of photonic structures including photonic bandgap crystals and spot size converters[6].

## References

[1] V. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, Nature 431, 1081 (2004).

[2] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, Princeton, NJ (1995)

[3]Almeida, V. R., Xu, Q., Barrios, C. A., and M. Lipson, "Guiding and Confining Light in Void Nanostructures using Field Discontinuity, Optics Letters, Vol. 29, n.11, June 1st, 2004.

4 Qianfan Xu, Vilson R. Almeida, Roberto R. Panepucci, and Michal Lipson, "Experimental demonstration of guiding and confining light in nanometer-size low-refractive-index material", Optics Letters 29, 1626 (July 2004)

[5] See for example L. D. Negro, M. Stol¯, Y. Yi, J. Michel, X. Duan, L. C. Kimerling, J. LeBlanc, and J. Haavisto, App. Phys. Lett. 84, 5186 (2004).

[6] M. M. Hler, B. J. Offrein, G. Bona, R. Germann, I. Massarek, and D. Erni, Journal of Lightwave Technology 16, 1680 (1998).