Silicon void nano-waveguides for guiding and confining light

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Abstract: We present theoretical and experimental evidence of a novel wavelength-insensitive waveguide geometry for guiding and confining light in nanometer-wide low-index materials, based on the discontinuity of the electric field at high-index-contrast interfaces.

OCIS codes: (230.7380) Waveguide, channeled; (130.2790) Guided waves

Guiding light in low-index materials such as air is thought to be prohibited in the conventional waveguides based on total internal reflection. Instead, external reflections from multiple dielectric layers [1,2] or photonic crystals [3] are usually used. However, these structures are wavelength-sensitive and have relatively large dimensions to provide the high reflections. Here we propose a waveguide structure that can confine light inside a nanometer-wide area of low-index material with high electric field intensity and high optical power density. In contrast to the leaky modes used in photonic crystals, the guiding mode is an eigenmode of the proposed structure and is therefore wavelength-insensitive and fundamentally lossless.

The principle of the novel structure is based on the discontinuity of the normal component of the electric field at the high-index-contrast interface, which is proportional to the square of the index-ratio across the interface. The proposed waveguiding structure, called slot-waveguide hereafter in this paper, is shown in Fig. 1. The waveguide consists of a nanometer-wide low-index slot with width w_s embedded between two rectangular high-index regions. For the quasi-TE mode, the major component of the electric field (which is horizontal) has a discontinuity at the walls of the slot (see Fig. 2). Since the dimension of the slot is comparable to the decay length of the field from the interface into the low index region, the electric field is high within the slot. The power density in the slot is much higher than that in the silicon region. The power transmitted in a sub-100-nm-wide slot can be higher than 40% of the total power when optimally designed. For the quasi-TM mode, with the major component of the electric field parallel to the walls of the slot, the effect of the slot is minimal.

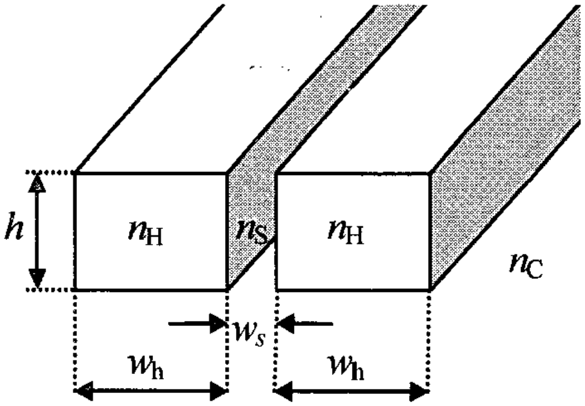

Fig. 1. Schematic of the slot-waveguide.

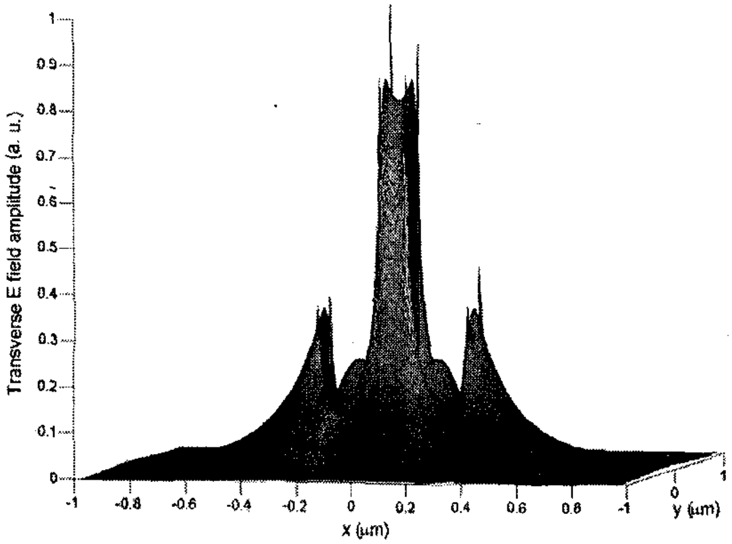

Fig. 2. Transverse electric field profile of the TE-like mode in a silicon-on-insulator-based slot-waveguide, when w_h = 218 nm, w_s = 101 nm, h =247 nm, n_H=3.48, n_S=1, and n_C=1.46. The dimensions are obtained from the cross-sectional SEM picture of the fabricated device. The origin of the coordinates system locates at the center of the waveguide, with a horizontal x-axis and a vertical y-axis.

In order to measure experimentally the effective indices of the modes in the slot waveguide, we fabricated directional couplers with slot waveguides (see Fig. 3), using a process similar to that described in [4]. The effective indices can be extracted from the dependence of coupling ratios on the distance between the slot-waveguides in the coupler. The measured effective indices are shown in Fig. 4, along with ones obtained using a full-vectorial finite difference mode solver [5]. The effective indices when there is no slot, i.e. $w_s = 0$, are also calculated. The effective index of the quasi-TM mode is affected very little by the presence of the slot. In contrast, the effective index of the quasi-TE mode is drastically reduced due to the presence of the slot, a direct evidence that the power is indeed concentrated in the low-index region.

In conclusion, we show experimental evidence that light can be guided and confined in low-index materials using field discontinuity in high-index-contrast material systems.

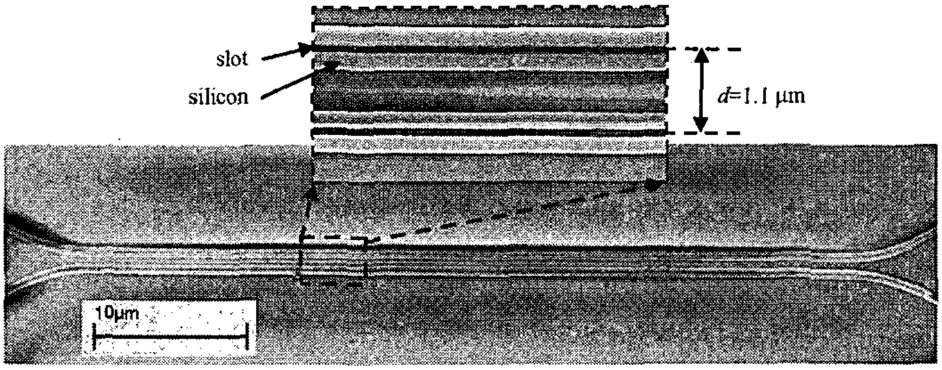

Fig. 3. The top-view SEM picture of a direction coupler formed by the slot-waveguides, fabricated with the silicon-on-insulator platform.

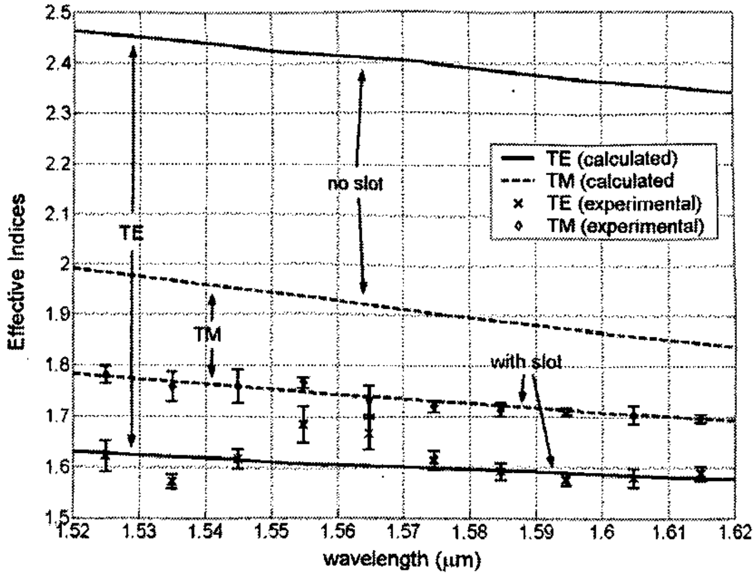

Fig. 4. The measured (marks with error bars) and simulated (lines) effective indices of quasi-TE and quasi-TM modes in the conventional and slot-waveguide. The parameters are the same as those in Fig. 2, except that $w_s = 0$ for the conventional waveguide.

References

1. S. G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. D. Engeness, M. Soljacic, S. A. Jacobs, J. D. Joannopoulos, and Y. Fink, "Low-loss asymptotically single-mode propagation in large-core OmniGuide fibers," Optics Express **9**, 748-779 (2001).
2. H. Schmidt, Y. Dongliang, and A. Hawkins, "Integrated optical spectroscopy of low index gases and liquids using ARROW waveguides," in *Integrated Photonics Research*, OSA Technical Digest, (Optical Society of America, Washington DC, 2003), ItuC2.
3. R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russel, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science **285**, 1537-1539 (1999).
4. V. R. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," Opt. Lett. **28**, 1302-1304 (2003).
5. C. L. Xu, W. P. Huang, M. S. Stern, and S. K. Chaudhuri, "Full-vectorial mode calculations by finite difference method," IEE Proc.-Optoelectron. **141**, 281-286 (1994).