Sub-100-nm Light Confinement in Transparent Photonic Wires

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Abstract

We directly measure the field confined in an 85 nm gap in a silicon slotted waveguide using a nanoscale probe to locally perturb the phase velocity of the light. We detect this perturbation interferometrically on-chip.

Summary of Research

Trapping light to regions much smaller than its wavelength greatly enhances interaction between light and matter [1]. This enhanced light matter interaction forms the basis for many photonic devices including lasers, sensors, and modulators. Typically light confinement is limited to a half wavelength in the propagation medium (\(\lambda/2n\)). Surface plasmon modes in metals provide the means to achieve light confinement in regions of cross sectional dimensions less than \(\lambda/2n\), however this usually comes at the cost of increased optical loss due to absorption by the metal [2, 3].

Recently it was theoretically shown that a nanoscale slot in a silicon waveguide could, in principle, achieve loss-less light confinement of less than \(\lambda/15\) in air [1, 4] by utilizing the electric field discontinuities at the boundaries of high-index-contrast waveguides. An example of such a structure with an 85 nm slot is shown in Figure 1a. Figure 1b plots the fundamental TE mode showing clear confinement of light to the slot region. While evidence of sub-100 nanometer light confinement has been reported from light emission of materials embedded in the slot [5], direct measurement has remained beyond the ability of near field measurement techniques: aperture near field scanning optical microscope (NSOM) probes are larger than the nanoscale slot, and apertureless NSOM techniques are primarily sensitive to the component of the field not confined in the slot region [6, 7].

To overcome the limitations of current near field measurement techniques we employ a novel transmission-based near field scanning optical microscopy (TraNSOM) technique which is based on changes in transmission through a photonic structure induced by near field perturbation by a nm-scale atomic force microscope (AFM) probe [7]. The probe used in our experiment is a Veeco high aspect ratio silicon shown in Figure 2. To ensure that the measurement is polarization independent, we measure the waveguide in an unbalanced Mach-Zender interferometer (MZI) configuration where we detect changes in transmission resulting from the probe-induced change in phase velocity.

Figure 1: (a) SEM of a slot waveguide; (b) calculated fundamental TE optical mode.

Figure 2: High aspect ratio Si AFM probe used to map the optical field.
The MZI used in this experiment was fabricated in 250 nm thick silicon on insulator using electron beam lithography and reactive ion etching. The device is approximately 250 µm long consisting of one arm with a 300 nm wide reference waveguide, and another arm with a 450 nm wide waveguide with a 85 nm slot (measured at the waveguide center using a scanning electron microscope (SEM)). To measure the change in phase velocity we measure the power transmitted through the MZI as a function of probe position. At the wavelength chosen for this experiment (1524.5 nm) this change in transmission is proportional to the local magnitude of $|E|^2$, therefore we construct a 2D profile of the optical mode.

Figure 3a shows the topography of the slot waveguide as measured by the AFM and Figure 3b shows the simultaneously recorded transmitted power. The large increase in transmission when the probe is in the slot is a direct measurement of the strong electric field confined in this region. Note that we have chosen a wavelength where the phase in the slot waveguide leads that of the reference waveguide by $\pi/2$. Therefore, decreasing the phase velocity in the slot waveguide with the silicon probe increases the total transmittivity.

Choosing this wavelength, where transmission increases under the influence of the probe, ensures that the dominant effect of the probe is indeed from a phase shift and not increased loss (which would result in a decrease in transmission at this wavelength). The solid line in Figure 4 shows a cross section of the TraNSOM measurement. Notice the sharp peak of the field in the slot has 20 nm full width half-maximum which agrees with the theoretical phase shift (dashed line) computed by convolving the probe profile with the fundamental TE mode shown in Figure 1b.

This TraNSOM measurement represents, to our knowledge, the strongest light confinement measured in dielectric photonic structures. Devices based on this strong light confinement will benefit greatly by the increased light-matter interaction in the slot region.

References