Effects produced by metal-coated near-field probes on the performance of silicon waveguides and resonators

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We study the effects of metal-coated fiber near-field probes on the performance of nanophotonic devices. Employing a heterodyne near-field scanning optical microscope and analyzing transmission characteristics, we find that a metal-coated probe can typically introduce a 3 dB intensity loss and a 0.2 rad phase shift during characterization of a straight waveguide made in a silicon-on-insulator system. In resonant nanophotonic structures such as a 5 μm radius microring resonator, we demonstrate that the probe induces a 1 nm shift in resonant wavelength and decreases the resonator quality factor, Q, from 1100 to 480. © 2007 Optical Society of America

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Near-field scanning optical microscopy (NSOM) is a versatile technique commonly used for characterization of nanophotonic devices made of nanostructured dielectrics, metalodielectrics, and composites containing quantum-confined nanostructures [1–4]. For a correct interpretation of the images obtained with NSOM, a careful analysis of the near-field coupling into the probe and subsequent propagation should be performed [5,6]. Also, several recent theoretical investigations have been made to analyze the effect of the probe on the device under study [7,8], and it was proposed to use this effect for tuning photonic crystal resonators [9–11]. However, the effect of widely used metal-coated fiber near-field probes on the performance of nanophotonic devices under study has not been experimentally investigated in detail yet. In this Letter we perform *in situ* characterization of the effect of the probe on the channel Si waveguide and then extend the study by measuring the effect on a Si microring resonator device.

In our experiments we use a heterodyne NSOM based on the Nanonics MultiView-2000 head with a heterodyne detection system operating around the near-infrared wavelength of $\lambda = 1.55$ μm [12]. Cantilevered probes are made of tapered and bent optical fiber usually coated with metal (Al or Au) with a small opening of $\sim 100-200$ nm at the apex. The heterodyne NSOM detection system is an all-fiber Mach–Zehnder interferometer with a reference arm that includes a pair of acousto-optic modulators and a signal acquisition arm that consists of the lensed fiber used for coupling input light into the nanophotonic device under test, the device itself, and the near-field fiber probe manipulator. The optical field collected by the probe interferes with the optical field from the reference arm, producing an interference signal oscillating at the heterodyne frequency of 70 kHz. Detection and lock-in amplification are used to extract the amplitude and the phase of the near-field optical signal.

We perform, using FEMLAB software, finite-element method numerical simulations of a simple Si waveguide on silicon dioxide cladding layer. Due to computational complexity associated with a dense mesh, we simulate only a 2D model. Although this constraint prevents an exact quantitative match with experiment, such simulation provides some insights into the effects of an NSOM probe on a device under study. We use a 300 nm thick layer of Si with refractive index of $n_{Si} = 3.5$ on top of a 3 μm thick layer of SiO_2 with refractive index $n_{SiO_2} = 1.5$. For the probe geometry we use the following values: the probe diameter before coating is 400 nm at the tip, the taper angle is 30°, the Al coating has a thickness of 200 nm, and the opening diameter (i.e., the uncoated aperture) is 200 nm. We also model the same configuration geometry without the Al coating on the probe. Running the simulation, we observe that the coated probe significantly perturbs the propagating optical mode in the Si waveguide. It causes a significant loss in the form of both radiation loss and backscattered reflection loss; the latter is critically significant for active nanophotonic devices. The effects of the metal coating are explained by the large difference in the refractive index of the metal (primarily its imaginary part) compared with that of the waveguide cladding (i.e., air). Quantitatively, our simulations predict that the coated probe brought in contact with the waveguide introduces approximately 2.4 dB of intensity loss and a 0.6 rad phase shift. The influence of the uncoated probe with the same geometry is negligibly small. However, we observe that the intensity of light coupled to the uncoated probe is lower.

For the experimental investigation we use a Γ-shaped SOI channel waveguide with a height of 280 nm and width of 500 nm. Lensed polarization-maintaining fibers couple the TE-polarized light into the waveguide and collect the transmitted light from the waveguide output. We experimentally analyze the transmitted light by using our heterodyne detec-

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tion system to determine the influence of the probe on the complex field transmission of the waveguide. The output of the guided field is monitored *in situ*, while the NSOM probe scans the waveguide structure in the transverse direction, perpendicular to the direction of propagating waveguide mode. The experimental results of measured transmission fields with respect to the probe position x are summarized in Fig. 1, showing the near-field amplitude collected by the probe [Fig. 1(a)] and the amplitude [Fig. 1(b)] and phase [Fig. 1(c)] at the output of the waveguide. The measured effect of the scanning probe on the transmitted guided wave [see Fig. 1(b)] is 3 dB loss in intensity, which is in agreement with our modeling estimate of about 2.4 dB loss. The measured phase shift reaches a maximum of about 0.2 rad [see Fig. 1(c)]. Note that the peak values in Figs. 1(b) and 1(c) are shifted with respect to the Fig. 1(a) peak. This phenomenon was observed and explained before [13]. We find that although uncoated probes do not affect light propagation, they are not suitable for NSOM imaging, primarily due to excessive optical losses in the fiber bend of the cantilever and lower coupling efficiency.

The presence of optical feedback in resonant photonic devices causes multiple interactions between the propagating field and the near-field probe, and we expect a significant enhancement in the effect of the probe on the performance of these nanophotonic devices.

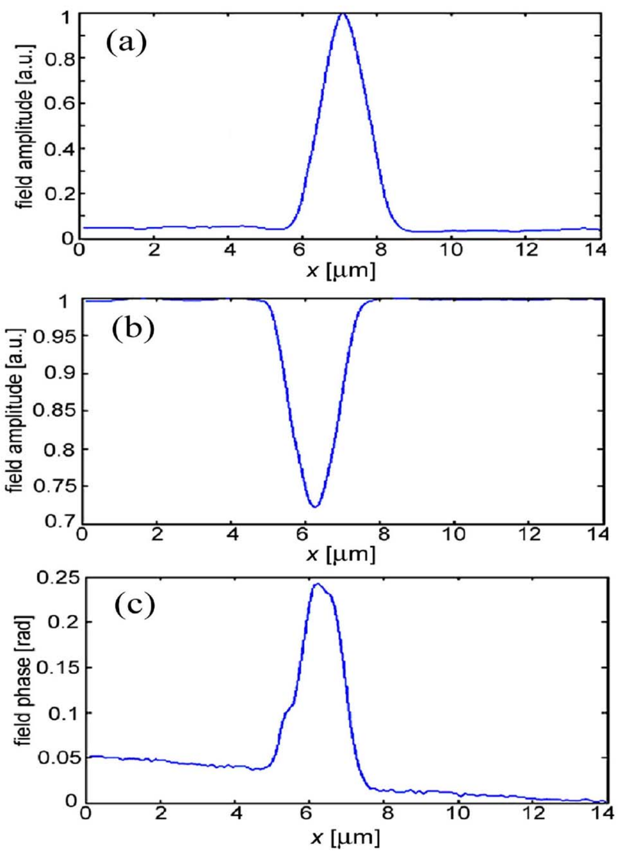

Fig. 1. (Color online) Effect of the position of the probe with respect to the center of the waveguide on the measured parameters: (a) amplitude of the optical field collected by the probe, (b) optical field amplitude, (c) optical phase at the output of the waveguide.

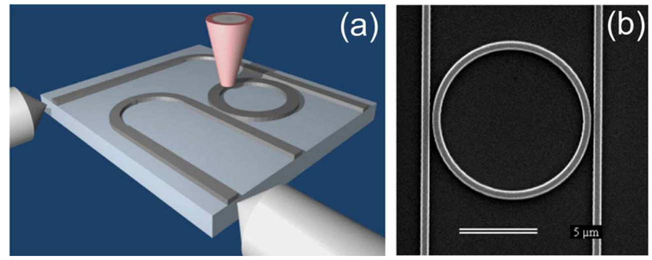

Fig. 2. (Color online) (a) Schematic diagram describing the experimental geometry; (b) scanning electron microscope micrograph of a microring resonator coupled to bus waveguides.

The aforementioned effect of the probe on a phase of the propagating optical field affects the resonance conditions. In addition, since the probe introduces loss, the quality factor of the resonator (Q) is expected to decrease as the probe scans the resonator device. For experimental validation of the effect of the probe on resonant devices, we choose to use Si microring resonators (see Fig. 2). Our resonant device has waveguide dimensions equal to the previous experiment; while the microring radius is 5 μm, the gap between the bus waveguides and the microring is 250 nm.

We find that at a fixed wavelength, as the probe scans the bus waveguides the output intensity always decreases because of losses similar to those observed in our waveguide experiment. However, when we scan the probe above the resonator, we observe either an increase or decrease of the transmitted light, depending on the wavelength of propagating light, which indicates that the probe causes a shift of the resonant wavelength. Quantitative experimental results of the effect of the position of the near-field probe on the transmission of the microring resonator are summarized in Fig. 3. Results of Fig. 3, curve (a), show that the resonance of the unperturbed structure occurs with a center wavelength of 1535.1 nm. Furthermore, when the probe is located above the bus waveguide, it has no effect on the center wavelength of the resonance [see Fig. 3, curve (b)]. However, when the near-field probe is located above the microring resonator, it locally increases the effective index of the ring and introduces a shift to the phase of the propagating light, causing the resonant wavelength to shift to 1536.1 nm [see Fig. 3, curve (c)]. The shift in resonant wavelength can be predicted by using the data obtained in the waveguide measurements. It is known that in one pass of the microring resonator the total phase change is

$$\varphi_{tot} = \frac{2\pi n_{eff} L}{\lambda}, \tag{1}$$

where n_{eff} is the effective refractive index of the Si waveguides. Neglecting the effect of the coupling region on the effective index of the waveguide, we can find an equivalent change in refractive index that produces the same phase shift as the probe:

$$\Delta n = \Delta\varphi \lambda_0 / 4\pi^2 R, \tag{2}$$

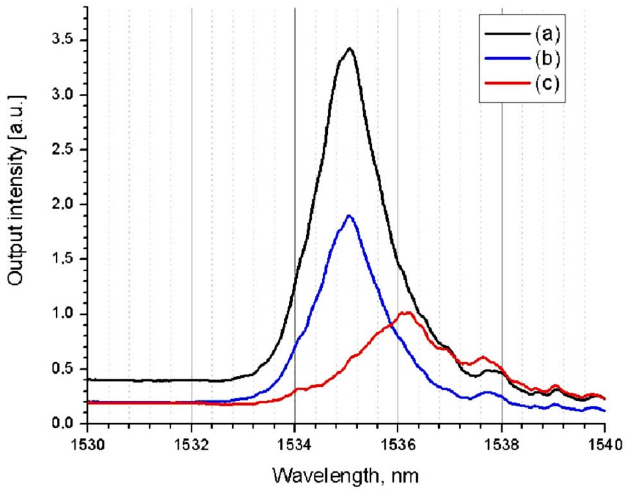

Fig. 3. (Color online) Spectral characteristics of the 5 μm radius ring resonator device: (a) near-field probe not in contact, (b) near-field probe in contact with bus waveguide, (c) near-field probe in contact with the microring.

where $L=2\pi R$ for the length of the resonator (radius $R=5$ μm). Substituting $\lambda_0=1535.1$ nm for the resonant wavelength and our experimentally measured phase shift introduced by the probe of $\Delta\varphi=0.2$ rad into Eq. (2), we obtain $\Delta n=1.56\times10^{-3}$. From Eq. (1) it follows that to keep resonant conditions, the ratio

$$\Delta\lambda/\lambda_0=\Delta n/n_{eff} \tag{3}$$

should be satisfied (note that n_{eff} is approximately 2.75 in our case). Thus $\Delta\lambda=0.87$ nm, which is quite close to the measured 1 nm shift. In addition to the redshift of the resonance wavelength, we also observe a significant decrease in the Q factor, which results from the loss introduced by the probe. This effect can be estimated from the relation

$$\frac{1}{Q}=\frac{1}{Q_{wop}}+\frac{1}{Q_{pr}}, \tag{4}$$

where Q_{wop} is the quality factor of the microring resonator without the presence of the probe. The quality factor associated with the power loss induced by the probe [14] is given by

$$Q_{pr}=4\pi^2Rn_{eff}/\alpha_{pr}\lambda_0, \tag{5}$$

where α_{pr} is the effective power loss coefficient due to probe–waveguide interaction. From the difference in the peak transmission in Fig. 3, curves (a) and (b), we estimate α_{pr} to be approximately 0.42, and we obtain $Q_{pr}\sim820$. The FWHM of the resonant peak in Fig. 3 curves (a) and (b) is about 1.4 nm, corresponding to a Q_{wop} of about $\sim$1100. Using Eq. (4) we estimate that the resonance in Fig. 3, curve (c), will have a quality factor of $Q\sim470$. This prediction is validated experimentally, where a $Q\sim480$ is calculated from the measured 3.2 nm FWHM (we included the ripple) for the resonance in Fig. 3, curve (c).

In conclusion, we suggest a method to investigate the influence of the optical near-field probe on the performance of guided wave devices and show that via electromagnetic coupling an NSOM probe can strongly modify the performance of operating nanophotonic devices. Performed 2D finite-element method numerical simulations show good agreement with experimental data obtained for SOI waveguides. Specifically, we find that for a 500 nm wide channel waveguide the metal-coated probe can introduce a 3 dB intensity loss and 0.2 rad phase shift. For resonant structures, as is predicted, the presence of the probe causes a shift of the resonant frequency and a decrease in the quality factor of the resonator. For a 5 μm radius microring SOI resonator, we find that the probe can induce a 1 nm shift of the resonance wavelength and decrease the resonator Q from 1100 to 480. These resonator parameters can be estimated by using the data obtained in the measurements of the effect of the probe on the Γ waveguide, suggesting an elegant way to analyze probe effects on complex nanophotonic devices by using simpler devices. Our investigation shows that the effect of the probe on the measurement needs to be considered, especially for reliable, characterization of resonant nanophotonic structures.

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References

1. L. Novotny and B. Hecht, *Principles of Nano-Optics* (Cambridge U. Press, 2006).
2. J. R. Guest, T. H. Stievater, G. Chen, E. A. Tabak, B. G. Orr, D. G. Steel, D. Gammon, and D. S. Katzer, Science **293**, 2224 (2001).
3. S. I. Bozhevolnyi, I. I. Smolyaninov, and A. V. Zayats, Phys. Rev. B **51**, 17916 (1995).
4. M. Abashin, P. Tortora, I. Märki, U. Levy, W. Nakagawa, L. Vaccaro, H. Herzig, and Y. Fainman, Opt. Express **14**, 1643 (2006).
5. L. Novotny, D. W. Pohl, and P. Regli, J. Opt. Soc. Am. A **11**, 1768 (1994).
6. A. Castiaux, A. Dereux, J.-P. Vigneron, C. Girard, and O. J. F. Martin, Ultramicroscopy **60**, 1 (1995).
7. M. Hammer and R. Stoffer, J. Lightwave Technol. **23**, 1956 (2005).
8. A. F. Koenderink, M. Kafesaki, B. C. Buchler, and V. Sandoghdar, Phys. Rev. Lett. **95**, 153904 (2005).
9. I. Märki, M. Salt, and H. P. Herzig, Opt. Express **14**, 2969 (2006).
10. B. Cluzel, E. Picard, T. Charvolin, E. Hadji, L. Lalouät, F. de Fornel, C. Sauvan, and P. Lalanne, Appl. Phys. Lett. **88**, 051112 (2006).
11. W. C. L. Hopman, K. O. van der Werf, A. J. F. Hollink, W. Bogaerts, V. Subramaniam, and R. M. de Ridder, Opt. Express **14**, 8745 (2006).
12. A. Nesci, and Y. Fainman, Proc. SPIE **5181**, 62 (2003).
13. J. T. Robinson, S. F. Preble, and M. Lipson, Opt. Express **14**, 10588 (2006).
14. J. Niehusmann, A. Vörckel, P. Bolivar, T. Wahlbrink, W. Henschel, and H. Kurz, Opt. Lett. **29**, 2861 (2004).