Metrology of integrated waveguide devices and systems using near-field scanning optical microscopy

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Abstract: Near-field scanning optical microscopy (NSOM) is a valuable tool for measuring modal propagation parameters including loss, effective index, and coupling coefficients of a variety of waveguide structures. Examples are provided of simple waveguide sections and bends as well as an on-chip optical clock distribution system using an H-tree containing splitters and leaky-mode polysilicon photodiodes.

1. INTRODUCTION

1.1 Motivation

Optical waveguide devices are essential components for photonic integrated circuits, on-chip optical interconnects, and integrated optical biosensors. Near-field scanning optical microscopy (NSOM) is a high resolution alternative to more traditional scatter imaging methods or cumbersome cutback studies for determining waveguide loss. It can easily resolve modal interference signals that can be used to determine propagation constants and related parameters. Several examples drawn from recently published work [1-3] are compiled to illustrate the power of this technique for analysis of integrated waveguide devices and systems.

1.2 Background on Near-field Scanning Optical Microscopy

NSOM is able to simultaneously measure surface topology and the optical intensity on the surface of optical systems. In particular in waveguide systems, the evanescent field at the interface to the air above the waveguide core or upper cladding is readily measured and related to the optical field intensity propagating in the waveguide. The measurements reported here were made using a commercial Alpha-NSOM system from WiTec with simultaneous optical and topological profiling capability. The experimental setup is shown in Fig. 1(a). The combination atomic force microscopy (AFM) and NSOM tip is a hollow aluminum pyramid integrated on a Si cantilever that converts the evanescent field to a propagating wave by locally frustrated total internal reflection. A photomultiplier tube is aligned to a subwavelength diameter pinhole centered in the tip to detect the wave emanating from the tip that is proportional to the evanescent field. A reference laser beam reflecting off the cantilever is directed to a quadrant detector by a dichroic beam splitter and is used to sense tip deflection in AFM mode. As the tip is moved toward the top surface of the waveguide, an exponentially increasing optical field, such as

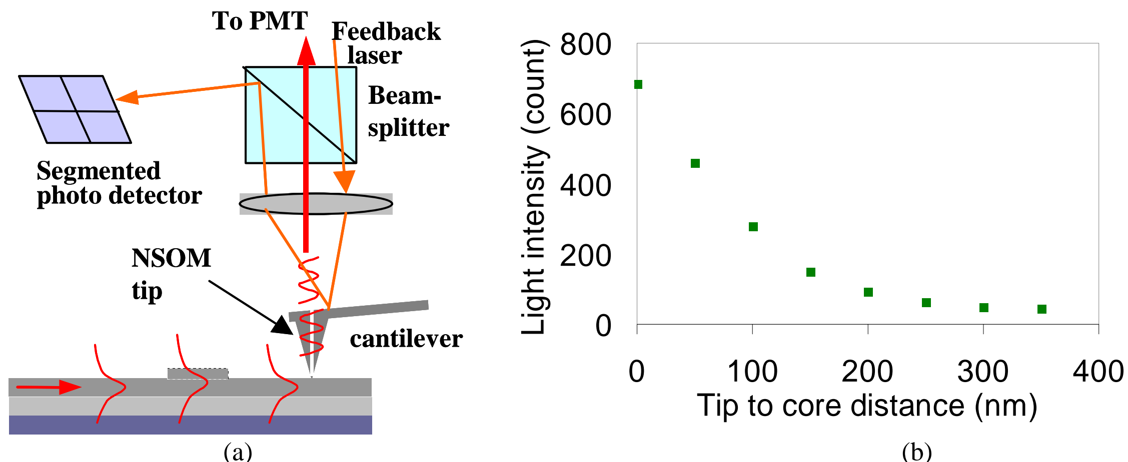


Fig. 1. (a) Schematic illustration of Witec Alpha-SNOM using optical detection of cantilever deflection, after [1]. The sample is scanned laterally. (b) An exponentially increasing optical field as the tip moving away from the top surface of the waveguide.

the measured data plotted in Fig. 1(b), is observed in addition to a constant background signal due to reference beam scattering. During in-plane optical profiling, the NSOM was operated in contact mode so that the field at the top surface of the waveguide was measured [1]. All of the measurements discussed below were performed by coupling a 654 nm laser diode to the waveguides under test using a visible single mode fiber with 4 µm core diameter.

2. MULTIMODE INTERFERENCE IN WAVEGUIDES

2.1 Single mode, straight waveguide

Prior to presentation of modal interference characterization in a few waveguide structures, it is useful to examine the measured topology and optical intensity distribution associated with a segment of straight, single-mode waveguides. The waveguide core was fabricated from a 105-nm-thick SiN film sputtered onto a ~2 µm thick SiO_2 lower cladding supported on a Si substrate. No solid upper cladding was deposited above the SiN to maximize the evanescent field interaction with the region above the core for biosensing purposes. This approach also provides the NSOM ready access to the evanescent field in the air above the core which serves as the upper cladding. Dry etching 21 nm of the SiN outside a ~2 µm-wide ridge defined the lateral extent of the core. The surface topology of the ridge, shown in Fig. 2(a), and the lateral intensity distribution of the evanescent field immediately above the core, illustrated in Fig. 2(b), were simultaneously acquired with the NSOM. The ridge appears wider than the nominal wavguide width due to the blunt nature of the probe tip around the optical aperture. The optical intensity pattern reveals a smooth, fundamental mode distribution without undulations associated with mode beating.

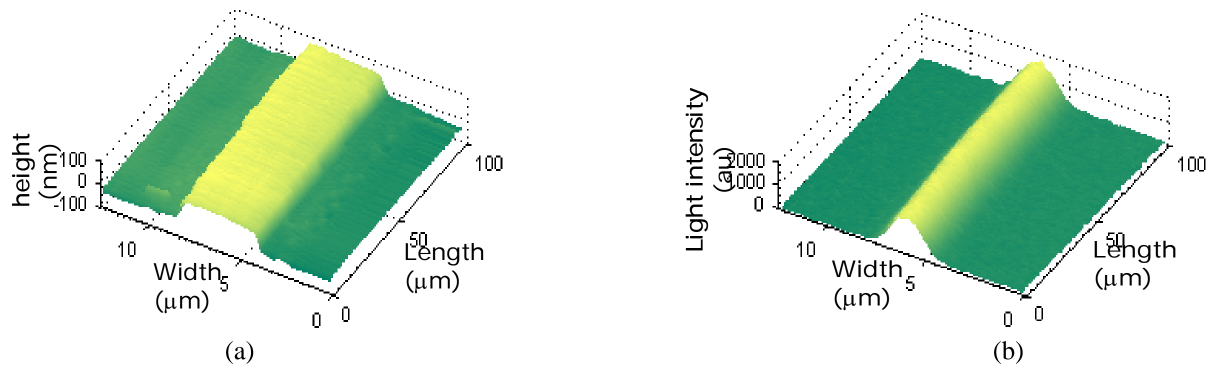


Figure 2: NSOM measurements of (a) surface topography and (b) optical intensity at the surface. Single mode observation is observed.

2.2 Multimode straight waveguides

Investigations of waveguides with larger dimensions revealed modal interference in waveguides. The surface intensity distribution of a ~4 µm wide waveguide, otherwise identical to the waveguide described above, resulted in multiple horizontally transverse modes seen in Fig. 3(a). The waveguide only supports two TE modes, TE_{00} and TE_{10}, according to modal calculations. The NSOM data in the figure shows the intensity maxima shifting back and forth laterally as the modes travel down the waveguide with different propagation constants. Another waveguide, 500 nm thick with a 250 nm ridge height, displayed interference between multiple orders of vertically transverse modes as seen in Fig. 3(b). The NSOM sees periodic extinction of the surface intensity when the modes are out of phase at the top of the waveguide. The beat distance is much smaller than in Fig. 3(a), indicating a larger difference in effective indices for the two modes.

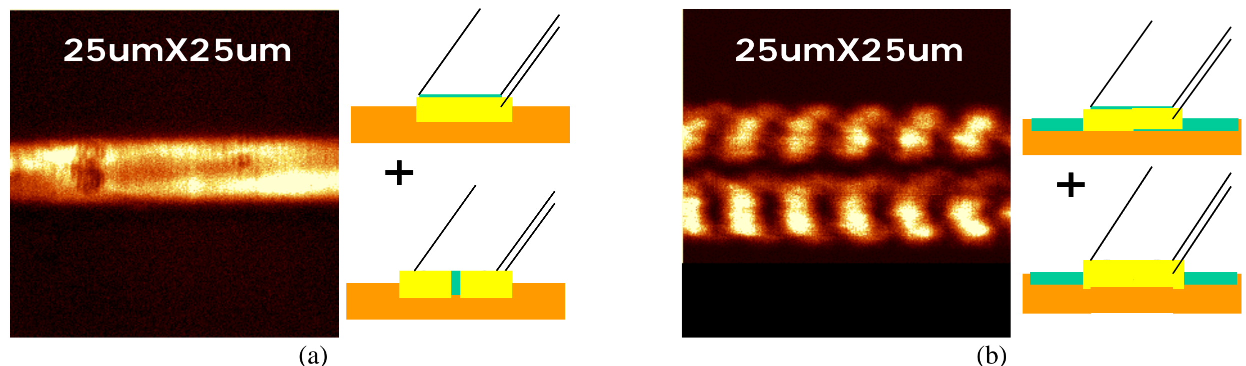


Figure 3: Surface optical intensity shows modal interference between the schematically illustrated modes for (a) 88 nm thick x ~4 µm wide waveguide core and (b) 88 nm thick x ~10 µm wide waveguide core.

2.3 Nearly single mode waveguide bend

More complicated structures, such as waveguide bends, also present the opportunity to study modal evolution and position and to extract propagation constant information the NSOM measurements [2]. The optical distribution in a ~4 µm wide waveguide similar to that described in Section 2.1 but with a shorter ridge was investigated in a 90° waveguide bend with a centerline radius of 400 µm shown in Fig. 4(a). Two bound modes in the bend determined from conformal mapping techniques matched those observed with NSOM. Simultaneous topography and optical measurements established the shift of the modes to the outside of the waveguide bend as seen in Fig. 4(b). Fitting of the transverse intensity profile at various angles along the bend allowed the determination of the relative intensity and phase of the two modes. The fitting procedure gave attenuation losses of the fundamental and the first order mode as 0.46 dB/90° and 15.1 dB/90°, respectively, demonstrating the effectiveness of planar waveguide bends for mode stripping. Interesting scattering patterns were observed at the exit of the bend to a straight waveguide where the radius of curvature and thus lateral eigenmode peak position shifts abruptly.

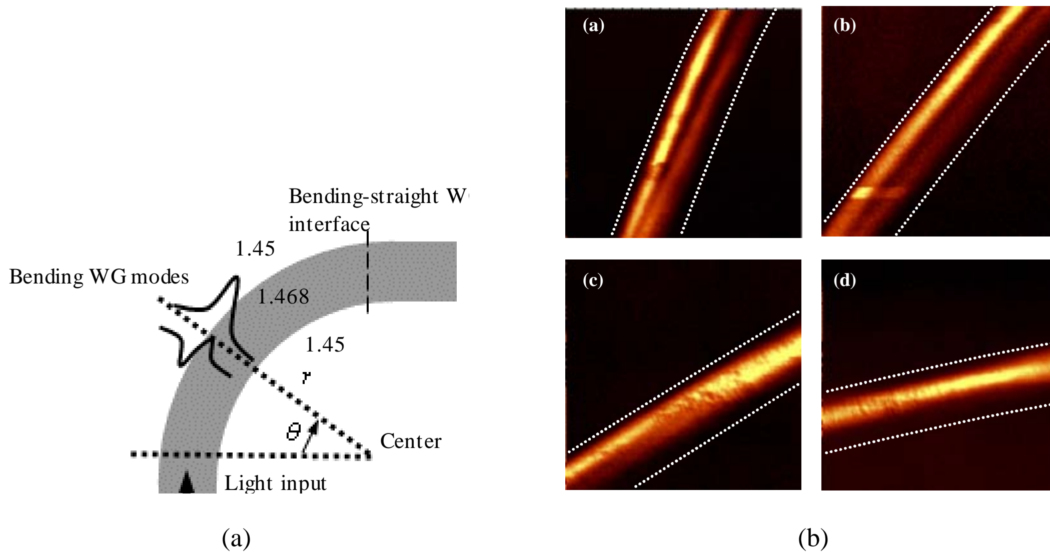


FIG. 4. (a) Schematic diagram (not to scale) of a 90° waveguide bend connected to straight input and output sections. (b) NSOM images of optical intensity at (a) 20°, (b) 40°, (c) 60°, and (d) 80° from the start of the waveguide bend. Dotted lines denote the waveguide core boundaries determined from simultaneous topographical scans. Reproduced from [2].

3. ON-CHIP OPTICAL INTERCONNECTS

A more complicated CMOS based, integrated waveguide optical system for on-chip clock distribution provided an environment for further NSOM studies [3]. The chip contains a series of waveguide straight sections, splitters, and bends in the form of an H-tree as illustrated in Fig. 5(b) to deliver an optical clock signal to 16 nodes where a leaky-mode detector converts the optical signal to photocurrent. Fig. 5(a) depicts the structure of the leaky-mode detector in an initial single metal level chip fabricated in Avago's 0.35 µm CMOS line in Fort Collins, Colorado. Scatter from the waveguides and detectors associated with four nodes is seen in Fig. 5(c). The SiN core waveguides are all 350 nm thick, with the width after the input taper decreases from to 8 µm down to 0.5µm. In contrast to the waveguides described in Section 2, this system did include a thin upper SiO_2cladding whose minimal 250 nm thickness still provided sufficient evanescent field strength at the air interface to allow NSOM measurements.

Optical intensity recorded along the H-tree was used to extract the loss and performance of the waveguides, splitters, and detectors. NSOM provides a higher resolution alternative to scatter imaging more commonly used for such studies. The first generation splitters had a high excess loss of 2dB or higher with forward scatter, mode beating in the outputs, and undesired unequal branching ratios as seen in Fig. 5(d). Revised designs for a second generation chip now being fabricated are aimed at addressing these issues. NSOM also proved valuable for investigating the coupling of light from the waveguide into the leaky mode detector and in particular determining the effective absorption coefficient of the polysilicon metal-semiconductor-metal detectors. Fig. 5(e) is the NSOM image of the detector region and the waveguide feeding it. Data taken from the centerline intensity is plotted in Fig. 5(f) where the detector portion has been fit to determine the effective absorption coefficient. The measured value of 0.67 dB/µm agrees very well with a calculation of 0.68 dB/µm and is 25 times higher than previously recorded values for leaky mode coupling to Si detectors [3]. Mode beating between the leaky mode centered in the SiN core

and radiation modes generated by the mode mismatch result in a beat signal seen in the decaying optical intensity on the surface above the detector seen in Fig. 5(f).

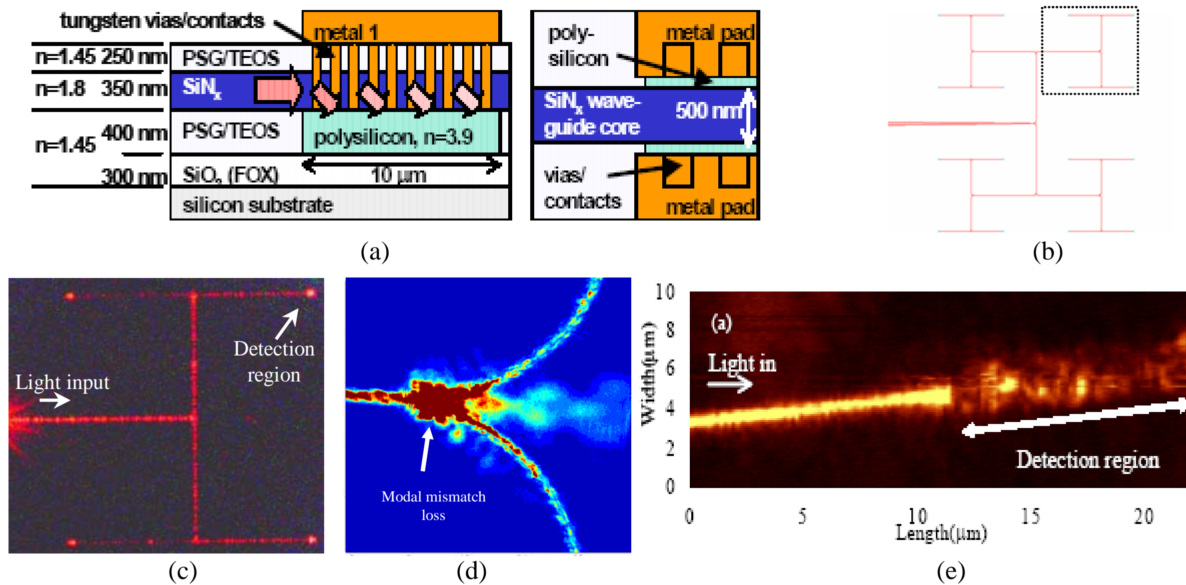
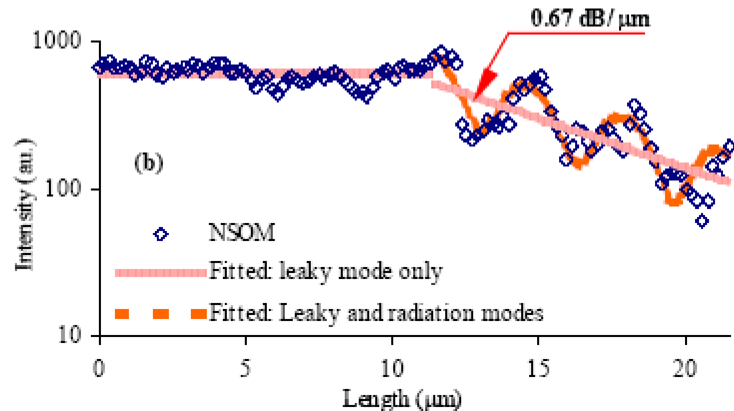


Fig.5. (a) Cross-sectional (left) and top view (right) diagrams of the waveguide and photodetector. (b) Diagram showing 16 node waveguide H-tree. (c) Microphotograph of the scattered light from a portion of the H-tree (indicated by the dashed line in part (b)). NSOM measurements of the light intensity at (d) one T-splitter of the H-tree and (e) waveguide and detector region. Note that the horizontal and vertical scales are different. (f) Intensity distribution on the waveguide and detector centerline from measurements (diamonds), fit to leaky and radiation modes (dashed), and fit to only the leaky mode (solid). Some portions reproduced from [3].



In addition to the systems described above, NSOM has been used to characterize the performance of a novel integrated waveguide biosensor that relies on local detection of evanescent fields [1], which is very similar to the mechanism of NSOM itself. Further, 1-D effective index models that are in good agreement with wide-angle beam propagation method (BPM) simulations have been developed that offer insight into the function of the leaky mode detectors as well as the new biosensor.

In summary, NSOM is a valuable tool for measuring modal propagation parameters in integrated waveguide structures. Further development of this technique including investigation of methods for accurately relating the surface intensity to the waveguide power in heterogeneous structures is warranted in view of the expected continued development of photonic and optoelectronic integrated circuits.

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