# Characterization of a 90° waveguide bend using near-field scanning optical microscopy

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**Abstract:** Multiple modes are directly imaged in a silicon nitride waveguide bend using near-field scanning optical microscopy (NSOM). The observations are in good agreement with modal calculations using conformal index transformation.

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## 1. Introduction

Waveguide bends are frequently used in photonic integrated circuits and optical sensors. Several theoretical models have been used to investigate modes in waveguide bends. Among them, the conformal index transformation method is regarded as a simple and effective method to solve for the mode profile. Our work reports experimental observations on the evolution of modes in waveguide bends for the first time [1].

To characterize a waveguide bend, near-field scanning optical microscopy (NSOM) is used to directly measure the evanescent field on the upper surface of a waveguide. The NSOM instrument used is an α-SNOM system from WiTec that is able to simultaneously measure light intensity and surface height [2]. The system has a lateral-scanning resolution of approximately 10 nm. The 90$^o$ waveguide bend studied here was fabricated using traditional sputtering, optical lithography, and etching processes. The 110 nm thick waveguide core of index 1.8 is made of $SiN_x$ and sits on a 2 μm-thick $SiO_2$ lower cladding of index 1.45 deposited on a Si wafer. A 4 μm wide rib waveguide was defined by partially dry etching the surrounding $SiN_x$ layer to a thickness of **ZZ** nm. The waveguide centerline bend radius is $R_c$ = 400 μm. 2-D effective index conformal mapping is sufficient to determine the lateral mode profiles. The waveguide core region has an effective index of 1.468 surrounded by a region with an effective index of 1.45, as illustrated in Fig. 1. The inner radius of the core is $R_1$ = 398 μm and the outer radius is $R_2$ = 402 μm. The angle between the interface where the straight waveguide enters the bend and the position studied is θ.

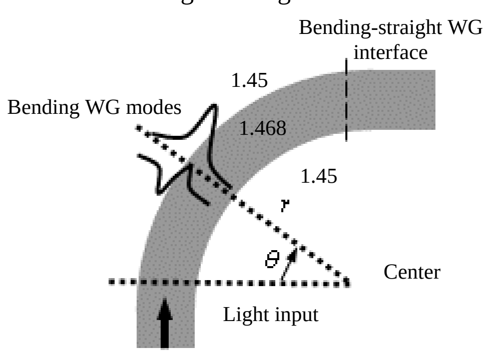


**FIG. 1.** Schematic diagram (not to scale) of a 90$^o$ waveguide bend connected to straight sections. The effective index of the waveguide core and cladding regions are 1.468 and 1.45. The waveguide bend supports two guided modes.

## 2. Experimental results and modal calculation

NSOM measurements simultaneously yielded light intensity and topography images, allowing the lateral mode position in the waveguide to be determined. Fig. 2 illustrates the intensity distribution in the bending waveguide segments centered at θ=20°, 40°, 60°, and 80°, with dotted lines showing the measured topographic edge of the ridge. Each scanned area is 25 μm × 25 μm. Strong modal interference is observed at 20°, but diminishes further along the bend. Although the bent waveguide supports a fundamental mode (m = 0) as well as a higher order mode (m = 1), the latter attenuates much faster than the fundamental. At larger angles (θ=60° and 80°), modal profiles become smooth, as the fundamental mode dominates the beam profiles.

A conformal index transformation based on new coordinate parameters $u(r) = R_2 \ln(r/R_2)$ and $n(u) = n(r)e^{u/R_2}$ were used to solve for the waveguide modes in the bend. The evolution of the transverse mode profiles are illustrated in Fig. 3. The measured values at different angles are shown as points, and theoretical fitting curves are shown as solid lines. The intensity profiles clearly show the presence of multimode interference which decays along the length of the bend. In particular, at 80° the mode profile is dominated by the fundamental mode. To extract the attenuation coefficients for the two modes, $\alpha_0$ and $\alpha_1$, in the presence of interference, the total magnetic field due to the interfering modes is expressed as $H(\theta,r) = A_0 H_0(r) exp(i\beta_0 R_c\theta - \alpha_0 R_c\theta) + A_1 H_1(r) exp(i\beta_1 R_c\theta + i\phi - \alpha_1 R_c\theta)$, where $A_0$ = 0.96 and $A_1$ = 3.4 are the relative amplitudes of the two modes, $H_m(r)$ is the transverse field distribution of the $m^{th}$ mode, and $\phi$ = 0.74π is the relative phase difference in the modes at the start of the bend. Relative amplitudes of these modes are obtained by fitting the measured NSOM intensity profiles. By fitting the evolution of the profile as well as the combined intensity, it is estimated that the attenuation loss of the fundamental and the first order mode are 0.46 dB/90° and 15.1 dB/90°, respectively, demonstrating the effectiveness of planar waveguide bends for mode stripping.

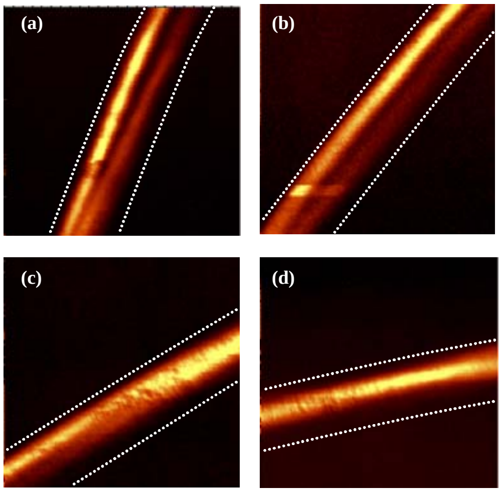


**FIG. 2.** NSOM images of optical intensity at (a) 20°, (b) 40°, (c) 60°, and (d) 80°, from the start of the waveguide bend. Dotted lines denote the waveguide core boundaries. As determined from simultaneous topographical scans.

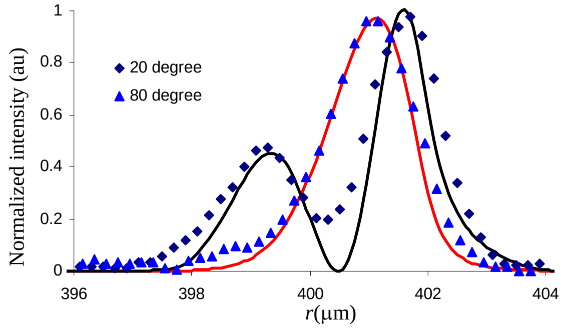


**FIG. 3.** Optical intensity distributions at different positions. Points are NSOM experimental data and solid curves are the theoretical fit.

## 3. Summary

In summary, near-field scanning optical microscopy was employed to directly image the modes in a waveguide bend. Interference between the two lowest order modes was observed and fit to obtain the relative amplitude, phase, and attenuation coefficients of the two modes. Conformal mapping of the index profile predicts the modal profiles accurately. The authors would like to thank NIH for sponsorship via Grant No. EB00726.

## 4. References

[1] G.W.Yuan,M.D. Stephens, D.S. Dandy, K.L. Lear, “Characterization of a 90° waveguide bend using near-field scanning optical microscopy," 191107, Vol. 87, Applied Physics Letters, Oct. 2005.

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