Demonstration of mode conversion in an irregular waveguide

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Communications wavelength waveguide mode conversion is demonstrated in an irregular metal-walled structure that was designed by using multiresolution optimization. Strong scatter and a large number of degrees of freedom allowed high-efficiency conversion in a device having a length of just a few wavelengths. The fabrication approach draws on standard semiconductor processing. Mode-selective reflectors, splitters, phase shifters, and other elements can be achieved by using this principle. © 2006 Optical Society of America

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Periodic structures such as photonic crystals form bandgaps in a way analogous to electrons in a crystal. Subwavelength aperiodic gratings have been used for polarization and phase control. We demonstrate here another mechanism for controlling light, which has more degrees of freedom and employs a conducting-wall waveguide with stepwise transverse dimension variations that excite significant evanescent field content. We have previously shown in a microwave waveguide that high-efficiency mode conversion could be obtained. The degrees of freedom available allow control over scatter, compact devices, and new functionalities such as mode-selective reflectors and phase shifters.

A schematic diagram of the proposed uniform-height optical waveguide structure is shown in Fig. 1(a), where the dielectric SiO₂ is surrounded by metal and is used to support the metal. Light is incident on one side, and the transformation is achieved on the other side. To model this geometry, the waveguide is divided into several sections, where the width and length of each section are parameters in the synthesis; in the design a cost function is minimized. The electromagnetic field problem is solved by the mode-matching method. To find an optimized structure, a multiresolution approach is used, whereby the structure is defined by successively finer features. The sidewall profile for a 1550 nm device is shown in Fig. 1(b). An incident TE₁₀ mode from the left is almost totally converted to a transmitted TE₃₀ mode, leaving from the right-hand side of the device. This element, while transforming the incident TE₁₀ mode to the output TE₃₀ mode at 1550 nm, can also act as a mode filter or a mode-selective reflector by rejecting an incident TE₁₀ mode from the right and allowing an incident TE₃₀ mode to pass through at 1550 nm. This is a direct result of the reciprocity, and the function could be applied in a laser waveguide to control the lateral profile of the resonant mode, because it provides mode-dependent loss.

A liftoff fabrication procedure has been developed for building the mode control device. Using this in conjunction with electron beam (e-beam) lithography, we have been able to accurately define 100 nm features and achieve a smooth sidewall, allowing infrared devices to be built. The process starts with a Au-coated wafer, where the Au is serving as the bottom wall of the waveguide converter. The pattern of the waveguide mode converter is then defined by e-beam lithography, as shown in Fig. 1(b).
lithography with a bilayer resist recipe. After the lithography, 5.0 nm Cr and 100.0 nm SiO\textsubscript{2} layers are deposited consecutively to form the dielectric part of the converter. The Cr layer is used to improve the adhesion between the Au and the SiO\textsubscript{2} layer. The entire wafer then undergoes a lift-off process to form the basic structure of the element. A Ag film is then sputtered to cover the side and the top walls of the waveguide element. Figure 2(a) shows the scanning-electron-microscope (SEM) photograph of the SiO\textsubscript{2} waveguide element on Au before the Ag sputtering.

The uniform waveguide on the left of the element is single moded, which ensures that the field incident on the mode converter is the fundamental mode, which is TE\textsubscript{10} in this case. The uniform waveguide on the right is a multimode waveguide that supports propagating TE\textsubscript{10}, TE\textsubscript{20}, and TE\textsubscript{30}, but the TE\textsubscript{20} mode is excluded because of symmetry. Figure 2(b) shows a microscope photograph after the Ag-sputtering step for the structure shown in Fig. 2(a).

We made measurements on the mode converter by using a NSOM. An Al/Cr-coated fiber tip was used to excite the element from the left-hand side through evanescent coupling. A tunable laser diode with a polarization controller was used for excitation. The output light is on the right-hand side of the Ag strip (the central region) in Fig. 2(b). Another coated fiber tip with 100 nm resolution, mounted on a three-axis translational stage with piezo control, was used to probe the scattered light on the right. This probe was scanned laterally (in the X direction) at a series of heights (Y values) above the substrate. The probing fiber was tilted at 60° from the waveguide plane in order to effectively detect the radiation from the output aperture. The excitation and detection fiber tips were separated by more than 25 \( \mu \text{m} \). The shielding and orientation of the detection fiber, and its proximity to the output aperture, allowed effective discrimination of the field radiating from the output aperture of the mode converter.

Measured data taken at \( \lambda = 1550 \text{ nm} \) are shown in Fig. 3(a). The scanning coordinate system is indicated in Fig. 2(b), with \( X \) across the waveguide aperture, \( Y \) the direction perpendicular to the substrate, and \( Z \) the distance between the scanning fiber tip and the output aperture. We use differential distance (\( \Delta X, \Delta Y \)) in Fig. 3(a) because an absolute reference was not available. To determine the mode content we compared the measured data with those obtained from a two-dimensional plane-wave expansion based on an aperture field that is a superposition of TE\textsubscript{10} and TE\textsubscript{30} modes with two unknown complex coefficients. Image fields were used about the planar conductor at the bottom of the waveguide, with the influence of the thin dielectric layer ignored. By fitting the predicted data to the experimental results, we were able to arrive at an estimate for the mode content in the aperture.

An obvious characteristic of the radiation intensity of the TE\textsubscript{30} mode is that it features three lobes in the X direction instead of the single-lobe characteristic of the TE\textsubscript{10} mode. An example at \( \lambda = 1550 \text{ nm} \) is shown in Fig. 3(b), calculated with 98% power in the TE\textsubscript{30} mode.

![Fig. 2.](image)

**Fig. 2.** (Color online) (a) SEM photo before Ag sputtering. (b) Microscope photograph after Ag sputtering, with the fiber probe coordinates.

![Fig. 3.](image)

**Fig. 3.** (Color online) (a) Two-dimensional NSOM scan at \( \lambda = 1550 \text{ nm} \): \( \Delta X \) is the distance across the output aperture, and \( \Delta Y \) is the vertical displacement from the substrate. (b) Simulation at \( Z = 3 \mu \text{m} \). The data shown as white curves in both (a) and (b) were used to fit the mode content.
mode at $Z = 3\,\mu m$, which is where we estimate the experimental data to be taken. The radiation intensity in Fig. 3(a) decreases as the fiber tip is raised (increasing $Y$). The method we used to obtain the mode content is as follows. As a compromise, to reduce interaction between the tip and the substrate and yet retain important features and an adequate signal-to-noise ratio, we selected the measured data at $Y = 1\,\mu m$, shown as the white curve in Fig. 3(a). From a comparison with the predicted patterns, we estimate that this corresponds to an absolute distance of $1.5\,\mu m$ above the substrate, and we use these data from the model. These data are shown as the white curve in the simulation of Fig. 3(b). Using the phase of each mode from the theoretical simulation of the converter, we adjusted the relative amplitude of the TE$_{10}$ and the TE$_{30}$ modes and calculated the plane-wave expansion, thereby fitting the model to the measured data. We found that the result in Fig. 4, in which the power percentage $(\text{TE}_{30}:\text{TE}_{10}) = (98\%:2\%)$, fits the measurement nicely. Following the same strategy, we used equivalent data from measurement scans from 1540 to 1560 nm. The result is shown in Fig. 5. For $\lambda = 1546\,nm$ to $\lambda = 1560\,nm$, the trend of the measurement follows the simulation but starts to deviate more for $\lambda < 1546\,nm$. There are several issues, in particular, the finite metal conductivity, imperfect metal sidewall coverage, the uniformity of the SiO$_2$, and possibly fabrication tolerances, which could give rise to this discrepancy at shorter wavelengths.

We have experimentally demonstrated the possibility of mode conversion at optical wavelengths by using an irregular metallic waveguide structure. This concept could be expanded to all-dielectric waveguide structures to facilitate integration with other optical devices.

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