A Spot-Size Transformer for Fiber-Chip Coupling in Sensor Applications at 633 nm in Silicon Oxynitride

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Abstract - A mode-size adapter was designed, fabricated in SION/SiO₂ and tested. It consists of a laterally tapered SION waveguide having a step-wise decrease in thickness towards the taper point which may have up to 0.5 μm residual width.

Most work on spot-size transformers for efficient fiber-chip coupling has been done at 1550 nm on III-V semiconductor waveguides [1]. Only a few spot-size transformers in other materials systems have been reported, e.g. a tapered Si₃N₄/SiO₂ waveguide for matching the mode profile of a semiconductor laser at 1550 nm to that of a fiber [2]. SiO₂-based waveguides are typically low-contrast and can be designed to have mode profiles that are well-matched to those in a single-mode fiber, so that efficient coupling can be achieved using a simple butt-end configuration.

Our application is a chemo-optical sensor operating at 633 nm, where a single-mode fiber should be coupled efficiently to a high index-contrast ($\Delta n \approx 0.24$) silicon oxynitride (SION) on SiO₂ waveguide.

In principle, the approach of [2] could be applied, using an adiabatic linear lateral taper performing the transformation from a 'loose-mode' waveguide at the fiber end to the 'tight-mode' waveguide required by the sensor design. However, due to the smaller wavelength, very high-resolution photolithography would be required in order to fabricate a sufficiently sharp taper point. In our case, the minimum width of the taper point was approximately 500 nm, giving rise to large radiation loss. Since a smooth vertical taper (like in [3]) was not an option, a design was made based on a step-wise lowered taper point (fig. 1).

The most important restrictions on the design are: Si substrate with thermally grown SiO₂ buffer layer ($n_{\text{buffer}} = 1.457$, max. thickness $H_{\text{buffer}} = 3 \mu\text{m}$); tight-mode waveguiding layer in SION ($n_{\text{tight}} = 1.7$, $H_{\text{tight}} = 300 \text{ nm}$) using plasma-enhanced chemical vapour deposition (PECVD); tight-mode cladding and loose-mode waveguiding layer in PECVD SiO₂ ($n_{\text{loose}} = 1.463$, thickness $H_{\text{loose}} < 2.1 \mu\text{m}$ for single-mode operation); the loose-mode cladding is air. The tight-mode ridge waveguide has ridge height $R_{\text{tight}} = 50 \text{ nm}$ and width $W_{\text{tight}} = 4 \mu\text{m}$.

The design of the loose-mode waveguide is not simply obtained by maximizing the modal field overlap with the fiber (single-mode, 4 μm core diameter, 0.1 NA), since also the sensitivity to fabrication tolerances for refractive

Figure 1. Spot-size transformer with linear lateral taper, step-wise lowered and finite width taper point

Figure 2. Modal fields of loose-mode (left) and tight-mode (right) waveguides.

indices (± 0.001), layer thicknesses ($\pm 20 \text{ nm}$) and etching depths ($\pm 10 \text{ nm}$) should be minimized. Furthermore, lithography restricts the ridge width W_{loose} to be 4 μm minimum. This leads to optimum values $H_{\text{loose}} = 1.85 \mu\text{m}$ and ridge height $R_{\text{loose}} = 800 \text{ nm}$, resulting in a worst-case coupling loss of 1.3 dB.

The field distributions for the loose-mode and tight-mode waveguides, as calculated using a finite-difference 2D mode solver are shown in fig. 2. A 2D Beam Propagation Method (in combination with the Effective Index Method) was used to calculate the coupling loss from the fiber to the tight-mode waveguide. It appeared that the taper angle should be less than 0.45 degrees (length more than 500 μm). An example of such calculations is shown

Figure 3. BPM simulations of otherwise identical spot-size transformers having zero-length (left) and 100 μm (right) loose mode waveguide sections.

in fig. 3, where the length L_{loose} of the loose-mode waveguide was varied. At first sight, it is surprising to see that radiation loss is much larger in the case of non-zero loose-mode waveguide length. This can be explained however since there is no perfect match of the loose-mode field with the fiber field, which inherently causes excitation of radiation modes. However, in the first case, the high-index taper section is so

near to the fiber-chip interface, that most of these radiation modes couple back into the high-index region. This enhanced coupling effect is of limited value, however, since it is bought at the expense of increased requirements on (1) the lateral positioning accuracy of the fiber with respect to the taper and (2) the positioning of the taper point with respect to the fiber-chip facet. A lateral misalignment of 1.5 μm would cancel out the enhancement. However, in our case there is another reason for keeping the loose-mode waveguide section as short as possible: due to the limited buffer layer thickness, some of the light will leak from the loose-mode section into the Si substrate, giving rise to additional (polarization dependent) loss (TM: about 0.2 dB for a 100 μm section).

The final step is to optimize the height of the lowered taper point. It was found that the first step (from 'zero' to the lowered section) has far greater influence on the coupling efficiency than the second step. Since technological limitations impose a minimum step height of 50 nm, this value was chosen for the first step, leaving 250 nm for the second step.

Further subdivision of the latter step into smaller ones had little influence on the overall efficiency because the first step is dominant. The calculated coupling loss of the resulting structure is 2.5 dB, for optimum fiber alignment, with additionally 1 dB loss for 0.7 μm vertical or 1 μm lateral misalignment. Devices have been fabricated and tested. The coupling loss was measured to be 1.7 ± 1.3 dB. The large error margin is due to uncertainty in the measurement of intrinsic waveguide losses. The measured sensitivity to fiber misalignment (e.g. fig. 4) shows good agreement with calculated results.

Figure 4. Normalized coupled power versus fiber vertical offset

In summary: We have designed, fabricated and tested a spot-size transformer for fiber-chip coupling in SION/SiO₂, operating at 633 nm and requiring only moderate quality photolithography. The measured coupling loss of 1.7 ± 1.3 dB is in agreement with the calculated value of 2.5 dB.

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