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Polymer taper bridge for silicon waveguide to single mode waveguide coupling

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ABSTRACT

Coupling of optical power from high-density silicon waveguides to silica optical fibers for signal routing can incur high losses and often requires complex end-face preparation/processing. Novel coupling device taper structures are proposed for low coupling loss between silicon photonic waveguides and single mode fibers are proposed and devices are fabricated and measured in terms of performance. Theoretical mode conversion models for waveguide tapers are derived for optimal device structure design and performance. Commercially viable vertical and multi-layer taper designs using polymer waveguide materials are proposed as innovative, cost-efficient, and mass-manufacturable optical coupling devices. The coupling efficiency for both designs is determined to evaluate optimal device dimensions and alignment tolerances with both silicon rib waveguides and silicon nanowire waveguides. Propagation loss as a function of waveguide roughness and metallic loss are determined and correlated to waveguide dimensions to obtain total insertion loss for the proposed taper designs. Multi-layer tapers on gold-sputtered substrates are fabricated through photolithography as proof-of-concept devices and evaluated for device loss optimization. Tapered waveguide coupling loss with Si WGs (2.74 dB) was experimentally measured with high correlation to theoretical results.

1. Introduction

Silicon (Si) waveguides (WGs) are used as high bandwidth optical communication channels ($\lambda = 1300–1600$ nm) within integrated devices and are readily fabricated using traditional semiconductor manufacturing techniques [1,2]. The high refractive index of silicon ($n = 3.5$) ensures strong confinement of light within single mode (SM) waveguides that are typically a few hundred nanometers in size. Silica-based single mode fibers (SMF) are typically used as optical interconnection method of coupling light into and out of the Si WGs within integrated devices due to their ease of handling, flexibility, low loss, and high bandwidth capability. Direct coupling between Si WGs (NA > 3.0) and SMFs (NA < 0.15) results in high coupling loss ($\Gamma_C = 18.8$ dB) [3] due to the modal size and numerical aperture (NA) mismatch. Modal mismatch between Si WGs and SMFs can be observed through the mode profiles as shown in Fig. 1.

Si WG gratings are currently the normal method of coupling with theoretical and experimental coupling loss of 5.1 dB and 6.8 dB respectively with a limited operating bandwidth of 60 nm [4]. Grating couplers also demand long (> 100 μm) adiabatic Si WG tapers for horizontal WG expansion for efficient power transmission from nanowire (400 nm) WGs to 10 μm wide grating couplers, both requiring additional space on the photonic chip. Grating solutions also require almost-perpendicular SMF placement to the photonic chip for out-of-plane (surface) coupling, demanding vertical device space to allow space for SMF bundles with large (> 20 mm) minimum bend radius.

Investing in edge-coupling devices is essential in minimizing photonic chip and packaging footprint requirements and improving broadband functionality. The leading efforts in fiber-to-chip connectivity have been focused on on-chip solutions. Silicon-based tapers have been previously proposed as modal expansion devices for reducing coupling losses with external devices [5]. Vertical-stepped and multi-layer Si WG tapers physically expand the WG dimensions and its fundamental mode size before interfacing with SMFs [6]. Low loss converters can transform Si Wire WGs into large cross-section Si Rib WGs for improved (3.3 dB) mode conversion and coupling efficiency with SMFs [7]. Unfortunately, most of these devices require complex or non-CMOS compatible manufacturing steps for on-chip device incorporation.

The most promising edge-coupling method for silicon photonics is the utilization of inverse tapers. Inverse tapers delocalize the propagating mode by adiabatically tapering down the core allowing the mode to expand into a surrounding material, either

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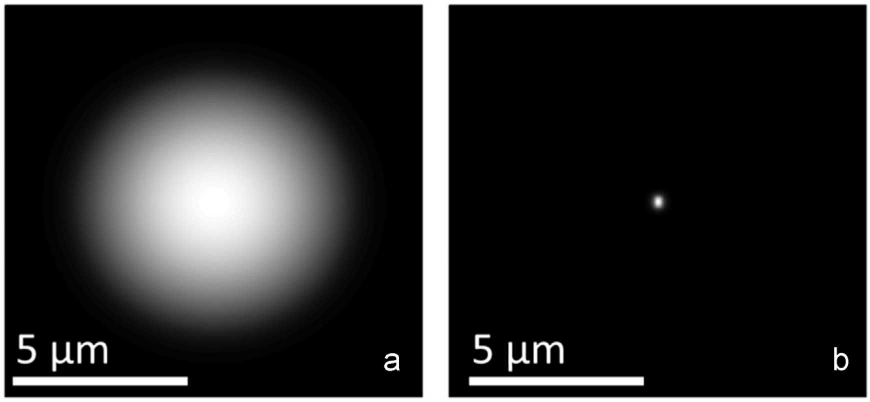

Fig. 1. Simulated mode profile [λ=1310 nm] of 8 μm diameter SMF (a) and 400 μm × 200 μm Si WG (b).

organic or inorganic, in the form of a large (> 3 μm) core dielectric WG [3]. Low index waveguides (3 μm × 3 μm) were previously shown in the literature to exhibit 2.5 dB coupling with 9.5 μm SMFs [8]. Inverse tapers require high quality and high resolution fabrication requirements to adiabatically shape the Si WG taper down to dimensions < 100 nm with long (> 100 μm) inverse taper lengths [9]. Furthermore, incorporating the large core dielectric WGs requires (> 1 μm) topography restricting and complicating the additional fabrication steps required on-chip [10].

To improve coupling efficiencies with on-chip mode conversion devices manufacturers shape the ends of SMFs. Tapered [11] and lensed [12] SMFs are utilized to reduce the output mode profile of the SMF reducing the modal overlap mismatch at the Si WG taper and SMF interface. Both designs require complex and expensive procedures to individually fabricate and align the optical fibers for coupling with Si WG arrays [13]. Alternatively, researchers have proposed an alternative coupling method utilizing Si WG tapers and overlapping polymer WGs with an MT connectivity but requires submicron overlapping distance tolerances for efficient evanescent coupling [14].

These modifications for Si WGs and SMFs require complex and costly procedures to accurately shape and cleave the mode-conversion end-faces of the optical interconnects [13]. Alternatively a Si-to-SMF bridge module is designed and implemented. The bridge module utilizing a novel WG taper design shown in Fig. 2 is manufactured using low loss waveguide polymer materials. This novel design reduces optical coupling loss and allows for system flexibility in device connectorization with direct contact with straight-cleaved optical interconnect end-faces. The bridge module was designed with the focus to eliminate the expenses required to manufacture mode-matching end-face devices on both photonic chips and long-haul optical fibers.

Polymer WG tapers are designed for symmetric planar coupling between Si WGs and SMFs. Polymer WG materials are ideal materials for mode-conversion devices as they exhibit low absorption loss and can be molded through a variety of cost-effective manufacturing techniques, including photolithography [15] and soft-imprint lithography [16]. Designs are evaluated in terms of manufacturability, coupling loss, length requirements, and alignment tolerances. A proof-of-concept polymer taper prototype is fabricated and low coupling losses are reported and contrasted to the simulation and modeling results.

2. Polymer WG tapers

2.1. Taper theory

Coupling efficiency, Γ_C, between two optical waveguides structures

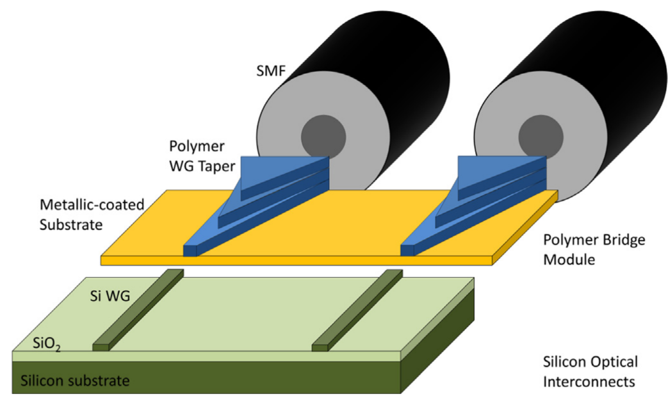

Fig. 2. Polymer taper bridge module illustration.

is calculated using an overlap integral [17] between the two mode profiles, as given by Eq. (1). Waveguide tapers implement a simplistic mode-expander to improve modal overlap with the WG devices by slowly transforming the fundamental mode as it propagates through the device. The polymer WG taper's capability to efficiency condense optical power to acquire significant overlap with Si WGs is determined by its NA. Tapers with a high NA (≥ 1.0) are required to acquire strong (< 1 μm mode profile width) modal confinement at the taper tip for effective overlap with the concentrated mode output of Si WGs, as shown in Fig. 3 [17]. The tapered region is surrounded by reflective metals or low dielectric materials to maintain a high NA and ensure modal confinement at sub-micron dimensions throughout the taper. While acting as a mode conversion device polymer WG tapers (NA∼1.1) still exhibit coupling loss at both end-faces with Si WGs (NA∼3.1) and SMFs (NA∼0.1).

$$\Gamma_C = \frac{\left|\iint E_{in}(x, y)E^{*}_{out}(x, y)dy\ dx\right|^2}{\iint |E_{in}(x, y)|^2 dx\ dy \iint |E_{out}(x, y)|^2 dx\ dy} \tag{1}$$

High NA polymer tapers tips with dimensions larger than the SM cutoff (0.8 μm for symmetric WGs, NA=1.1, λ=1310 nm) permit increasing levels of the excitation and propagation of higher-order modes within the taper. Higher mode structures experience modal interference resulting in modal dispersion. Each excited mode propagates at a different velocity inducing a fluctuating E-field that is a function of taper length. The significant differences in E-field fluctuations between single mode and multi-mode coupling within polymer tapers are shown in Fig. 4. The self-imaging effects of multi-mode interference create a varying output profile at the output of the tapered WG resulting in large deviations in device coupling if the length of the taper is not significantly controlled [18].