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TM grating coupler on low-loss LPCVD based Si_3N_4 waveguide platform

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ABSTRACT

We demonstrate, for the first time to our knowledge, a fully etched TM grating coupler for low-loss Low-Pressure-Chemical-Vapor-Deposition (LPCVD) based silicon nitride platform with a coupling loss of 6.5 dB at 1541 nm and a 1 dB bandwidth of 55 nm, addressing applications where TM polarization is a pre-requisite. The proposed GC and the 360 nm × 800 nm strip based Si_3N_4 waveguides have been fabricated by optical projection lithography using an i-line stepper tool enabling low-cost and mass manufacturing of photonic-integrated-circuits.

1. Introduction

Silicon-nitride based photonic integration technology has recently attracted momentous research interest as an attractive low-loss nanophotonic platform that, provides multiple benefits across a wide range of applications [1,2]. Silicon nitride waveguides can be fabricated in CMOS pilot lines with significantly lower cost than the Silicon-On-Insulator (SOI) waveguide platform, using either plasma-enhanced-chemical-vapor-deposition (PECVD) or LPCVD. Moreover, silicon nitride based waveguides cladded with silica offer a moderate index contrast, which renders the waveguiding mechanism less prone to scattering losses associated with the waveguide sidewall roughness. Therefore, silicon nitride waveguides exhibit propagation losses almost an order of magnitude lower than silicon waveguide losses [3], impelling their deployment as a low-loss nanophotonic platform for chip-scale transmission, filtering, multiplexing and biosensing applications [4].

Interfacing between silicon nitride nanophotonic platforms and fiber-based configurations is mainly performed by Grating Couplers (GCs) for out-of-plane coupling or by inverted tapers serving as spot size converters [5]. While the latter usually offers lower coupling loss, GCs enable wafer-scale testing with relaxed fiber alignment tolerances. So far, pure silicon nitride-based GCs have been reported only for TE polarization exhibiting coupling efficiencies slightly higher than 60% [6]. Despite the proven capabilities of SiN waveguides to support efficiently TM polarization [2], TM operating silicon nitride GCs still remain an unexplored territory impeding the exploitation of complementary optical functionalities that require TM-polarized light, as can be, for example, offered by plasmonic waveguides [7]. The low-loss characteristics of the Si_3N_4 waveguides can offer an ideal low-loss photonic platform on which plasmonic waveguides can be selectively deposited [8]; this can allow for the utilization of the proven integration density [8] and functional advantages of plasmonic waveguides in biosensors [9,10] or low-power switch setups [11,12], restricting the increased plasmonic propagation losses only to the high-functionality area and residing on the low-loss SiN platform for the additional passive functionalities required in a complete module.

In this work, we present for the first time to the best of our knowledge, the design and the experimental demonstration of a fully etched TM GC on a low-loss LPCVD silicon nitride waveguide platform at AMO. The proposed GC structure exhibited a coupling loss of 6.5 dB, a 1 dB bandwidth of 55 nm and an excess coupling loss of only 0.5 dB for a ±2 degrees fiber angle misalignment around the optimal angle of 37 degrees, while the 360 nm × 800 nm strip based Si_3N_4 waveguide exhibited propagation losses of 0.55 dB/cm at 1550 nm. Optical projection lithography and an i-line stepper tool were used to fabricate the Si_3N_4 structures. The proposed GC facilitates the effective co-integration of silicon nitride with TM-performing plasmonic waveguides [9,11], while its optical projection lithography-based deployment enables high throughput and low-cost fabrication for wafer-scale photonic-integrated-circuits (PICs).

2. Design and simulation

In our designs, we considered a 360 nm thick silicon nitride waveguide layer lying on top of a 2.2 μm thick thermally grown SiO_2,

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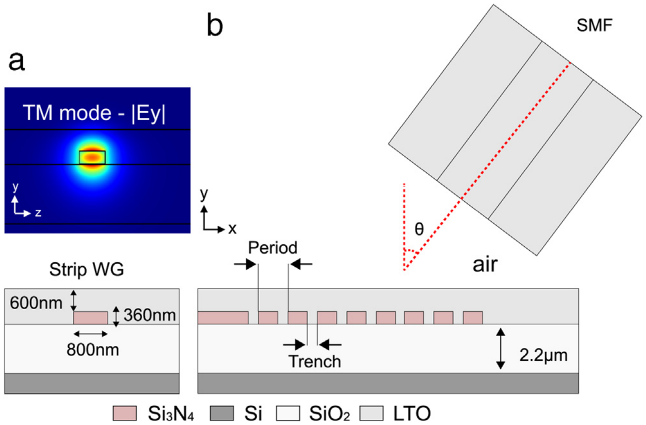

Fig. 1. (a) Cross-section view of the Si_3N_4 waveguide along with the supported quasi TM-mode profile and (b) Sideview of the proposed grating coupler structure denoting the grating parameters and the dimensions of the involved dielectrics.

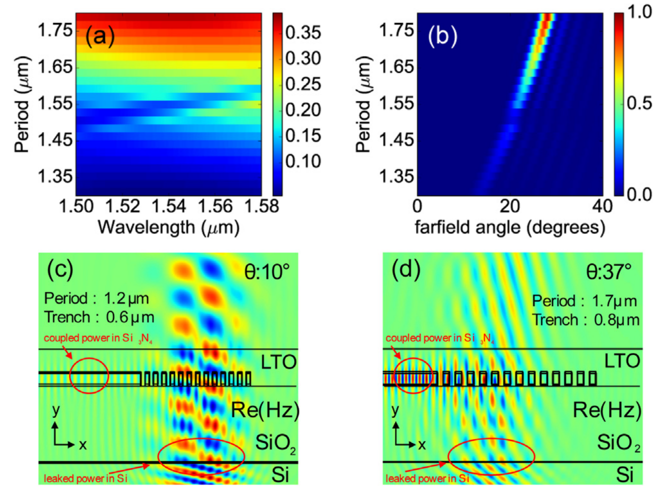

Fig. 2. (a) GC directionality as function of wavelength and (b) Far-field intensity as a function of far-field angle at 1.55 μm, for varied period lengths. (c) and (d) Magnetic field profiles (Re(H_z)) along the grating coupler structure illustrating the leakage of optical power into the Si substrate and the coupled power into the Si_3N_4 waveguide for a fiber angle of 10 and 37 degrees, respectively.

top cladded with 960 nm of Low-Temperature-Oxide (LTO). A cross-section view of the strip based Si_3N_4 waveguide supporting a quasi-TM mode is shown in Fig. 1(a). A fully etched TM-mode GC for straight cleaved single-mode (SM) fibers and 360 nm × 800 nm strip based Si_3N_4 waveguides has been designed and numerically simulated using a commercially available 2D FDTD solver package [13]. A schematic side view of the proposed GC is illustrated in Fig. 1(b).

The design procedure that has been followed in order to design a Si_3N_4 grating coupler structure for TM mode has been the following: In a first step, we designed a grating coupler targeting conventional angles around the value of 10 degrees. In order to satisfy the Bragg condition, the estimated period length for this angle of incidence has been calculated around 1.2 μm. The resulted coupling efficiency for this period length is rather poor (below 18 dB at 1.55 μm) mainly due to the large leakage of optical power into the Si substrate. This large leakage originates from the constructive interference, that takes place towards the Si substrate between multiple reflections in the grating coupler structure. More specifically, light beams being diffracted from the grating coupler towards the Si substrate enter the cavity that is formed between the Si_3N_4 layer and the Si substrate, and interfere constructively at the Si–SiO_2 interface, yielding increased optical power levels leaked into the Si substrate. In contrary, coupling loss reduces when destructive interference takes place between those reflections at the Si–SiO_2 interface, leading to reduced power levels leaked into the Si substrate and as such to higher power levels propagating towards the Si_3N_4 cladding layer. Reflections between the Si_3N_4, the top cladding layer and the surrounding medium also contribute to the interference pattern [14]. In our designs, all the dielectric thicknesses are determined by the exploited wafers and the available fabrication processes. Therefore, the only grating parameters that were available for engineering the effective index of the grating coupler were the period and the trench size. After a series of simulations, the grating parameters that satisfy the phase matching condition for having destructive interference at the Si–SiO_2 interface were identified, resulting in a grating effective index that reduces the leakage of optical power into the silicon substrate. Initially, we considered a coupling scheme, where the slab TM mode was launched into the waveguide and the directionality of the grating structure was examined for varied period lengths larger than 1.2 μm and up to 1.8 μm, using a fixed trench size of 800 nm. Fig. 2(a) presents the directionality simulation results for varied period lengths from 1.3 up to 1.8 μm with a fixed trench size of 800 nm. Fig. 2(b) presents the simulated far-field intensity as a function of the far-field angle at 1.55 μm into the GC top cladding layer, for varied period length. In this way, we scanned a large range of grating periods where destructive interference between the reflections at the Si–SiO_2 interface took place. The initial choice of a trench size equal to 800 nm has been made in order to comply with the fabrication requirements for a minimum feature size of 500 nm in the entire range of 1.3–1.8 μm grating period values considered under investigation. For instance, considering a grating structure with a period length of 1.3 μm and a trench size of 800 nm, the resulted grating tooth is at the fabrication resolution limit of 500 nm. This allowed us to explore a wide range of period lengths complying with the fabrication constraints. We preferred to keep the trench size constant and to vary the period length prior proceeding to fine tuning the trench size for every tested period length, since the effective index of the grating undergoes a higher modulation for period variations compared to trench size changes [14]. This means that the grating period is the most important grating parameter that has to be tuned in a first step, allowing for the coarse identification of the grating effective index value that minimizes leakage into the Si substrate given the provided design rules. According to the numerical results that are shown in Fig. 2(a), the GC directionality can exceed 30% at 1.55 μm for period lengths larger than 1.65 μm. A period length of 1.70 μm dictates a far-field angle of 25.8 degrees, suggesting a fiber angle of 37 degrees with respect to the GC's top surface, when air is considered as the surrounding medium. Figs. 2(c) and (d), illustrate the simulated magnetic field (Re(Hz)) and the interference pattern for period lengths of 1.2 μm and 1.7 μm that correspond to optimal fiber coupling angles of 10 and 37 degrees, respectively. In both cases, light was injected from the fiber into the Si_3N_4 structure with the aim of monitoring the power leakage into the Si substrate. As can be clearly seen, a much higher optical power value contributes to the interference pattern in the case of 10 degrees coupling angle, resulting to increased optical power leakage into the silicon substrate and lower coupling efficiency into the Si_3N_4 waveguide. By increasing the angle to 37 degrees and using the optimal 1.7 μm period length for this angle, according to the calculated far-field angles in the grating cladding shown in Fig. 2(b), the optical power that leaks towards the Si substrate is significantly reduced and higher power levels are coupled into the Si_3N_4 waveguide. This owes to the optimized effective index of the grating and the destructive interference achieved at the Si–SiO_2 interface.

The simulated coupling loss as a function of wavelength of the proposed GC for different period length values and a fiber coupling angle of 37 degrees is illustrated in Figs. 3(a) and (b). Simulations predicted a minimum coupling loss of 6.4 dB at 1560 nm, for a GC with a period length of 1.71 μm and a trench size of 800 nm. Peak coupling loss is