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Broadband and High-Performance Devices for the Silicon and Silicon-Nitride Platforms

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ABSTRACT

The increasing demand for higher data rates and small form factor equipment for optical networks is fuelling research on integrated optical devices with small footprint and broad bandwidth. Here, we present novel design approaches for grating couplers in the silicon and silicon nitride platforms that enable broadband operation and highly efficient coupling. Furthermore, we report experimental findings on compact integrated waveguide splitters that provide virtual perfect performance over more than 300 nm of bandwidth at telecom wavelengths.

Keywords: integrated optics, silicon photonics, multimode interference couplers, grating couplers, subwavelength structures

1. INTRODUCTION

Over the last years, the exponential growth of optical networks capacity has increased research in integrated optic technologies beyond the already mature III-V platforms. In this scenario, silicon photonics has emerged as a key technological platform to support the low cost and high performance requirements demanded by telecom and especially datacom networks. Photonic integrated circuits (PICs) with full C band operation are now widespread and there is an increased interest in devices covering several communication bands. Multimode Interference Couplers (MMI) and fiber-to-chip grating couplers are two of the basic building blocks of PICs. Thus improvement in bandwidth, uniformity and efficiency of these devices is a must. In this communication we review several designs of MMIs and grating couplers with improved performance. First, a broadband MMI covering more than 300 nm bandwidth will be presented which is based on a SWG structures to reduce the wavelength dependence of the beat length L_π. Then a SWG based zero-order prism-assisted grating coupler will be presented with a 1 dB bandwidth exceeding 125 nm. Finally, we will show how a self-imaging grating can be designed to obtain a highly efficient (0.66 dB total losses) grating coupler in a SiN platform in which it is difficult to achieve enough radiation strength to place the fiber in close proximity to the chip surface.

2. BROADBAND MULTI-MODE INTERFERENCE COUPLERS

Multimode interference couplers (MMIs) are basic building blocks in integrated optics, and have a wide range of applications, including spectroscopy chips, or high speed coherent optical receivers. The operation and design of MMIs has been extensively studied [1], but their operational bandwidth, while broad compared to directional couplers, remains fundamentally limited. There is, however, an increasing interest for broadband devices, both for vibrational fingerprint sensing in the Mid-Infrared region, as well as for novel communications systems covering several optical bands. Here we present a subwavelength structured MMI (Fig. 1a) in the silicon-on-insulator platform capable of ultra-broadband operation [2].

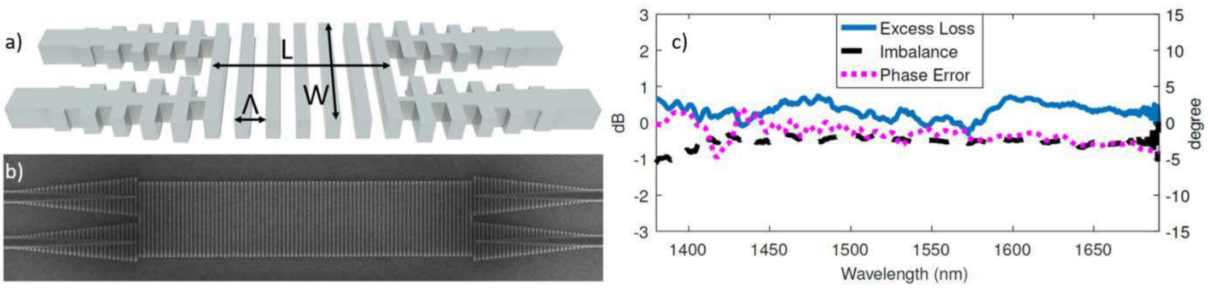


Figure 1: a) Schematic geometry of the ultra-broadband multimode interference coupler in silicon-on-insulator; b) Scanning electron microscopy (SEM) image of one of the fabricated devices; c) Measured performance revealing an operational bandwidth in excess of 300nm at telecom wavelengths.

The physical length (L) of MMIs is determined by the beat-length of the two lowest order modes propagating in the central wide multimode region (of width W) (see Fig. 1a). In conventional MMIs this beat-length is given by $L_\pi \approx (4W^2)/(3\lambda)\cdot n_c$, where n_c is the effective index of the multimode region and λ is the free-space wavelength. Due to the wavelength dependence of the beat-length, the device becomes detuned as wavelength is changed. In our device, we use silicon subwavelength structures (SWG) to overcome this limitation. SWGs behave as homogenous media and are extensively used in silicon photonics [3-5], including directional and adiabatic couplers with bandwidths between 100 nm and 130 nm [6,7]. In the SWG MMI we simultaneously exploit the anisotropy and dispersion of the subwavelength structure: the duty-cycle (50%) and pitch (Λ = 190 nm) are optimized to minimize the beat-length and its wavelength dependence [2]. The resulting device is only L = 14 µm long, and W = 3.25 µm wide and exhibits a potential bandwidth of more than 500 nm at telecom wavelengths as per 3D FDTD simulations.

Figure 1b shows a SEM image of one the fabricated devices in 220 nm thick silicon, prior to the deposition of the silicon dioxide cladding layer. The measurement results are shown in Fig. 1c confirming the high performance of the device over a bandwidth of 300 nm, with both excess losses and imbalance below 1 dB and phase error below 5º.

3. BROADBAND HIGH-EFFICIENCY ZERO-ORDER GRATING COUPLERS

The modal dimensions of photonic waveguides in high-index contrast platforms like silicon-on-insulator (SOI) are small compared to optical fiber cores. Consequently, coupling of light from optical circuits into optical fibers, or vice versa, is a major issue in integrated photonics. Surface grating couplers are common devices used to address this coupling problem. They comprise a periodic waveguide designed to radiate the input light towards the optical fiber. Unlike edge couplers, surface grating couplers do not require facet polishing and can be used for wafer-scale testing [8]. However, the radiation angle is strongly wavelength dependent limiting the bandwidth of surface grating couplers [9]. Several alternatives have been proposed to increase surface grating couplers, but generally at the expense of reducing their coupling efficiency. Here we present a subwavelength-engineered grating coupler that, only radiating in the zeroth order, mitigates the natural wavelength dependency of grating couplers and achieves a subdecibel coupling efficiency.

Figure 2a shows a 2D schematic representation of a zero-order grating coupler for the SOI technology. The structure consists in a high-index (n_u) prism with angle ϕ_{prism}, placed on top of a periodic waveguide of length L, pitch Λ and duty cycle $DC = a/\Lambda$, where a is the length of silicon segment. The prism is attached to the waveguide by an epoxy resin (n_e). A quarter-wave anti-reflection coating is employed to reduce the Fresnel reflection at the prism-to-air interface. An adiabatic taper adapts the input waveguide to the grating.

In conventional surface grating couplers, the radiation angle is given by the phase matching equation [10]

$$n_u \sin(\theta) = n_B + m\frac{\lambda}{\Lambda}, \tag{1}$$

where n_B is the real part of the effective Bloch-Floquet mode of the grating waveguide, λ is the operating wavelength, θ is the radiation angle and the integer m is the diffraction order. The upper material is usually air (n_u = 1) and therefore m must be negative to produce real radiation angles.

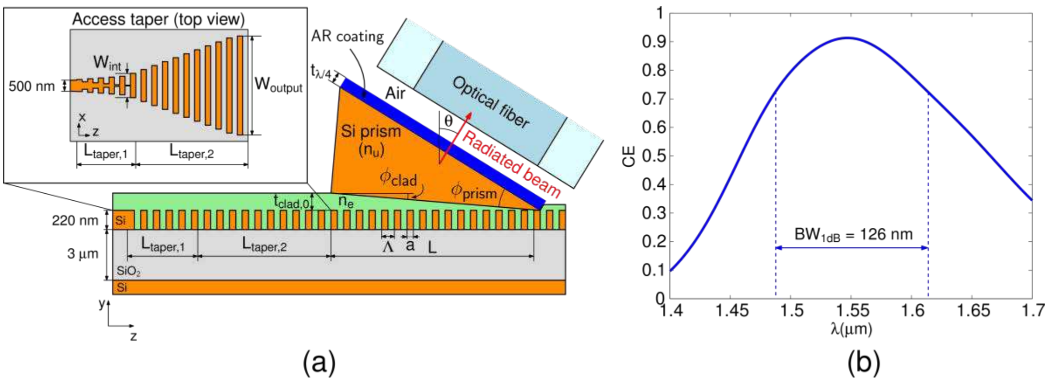


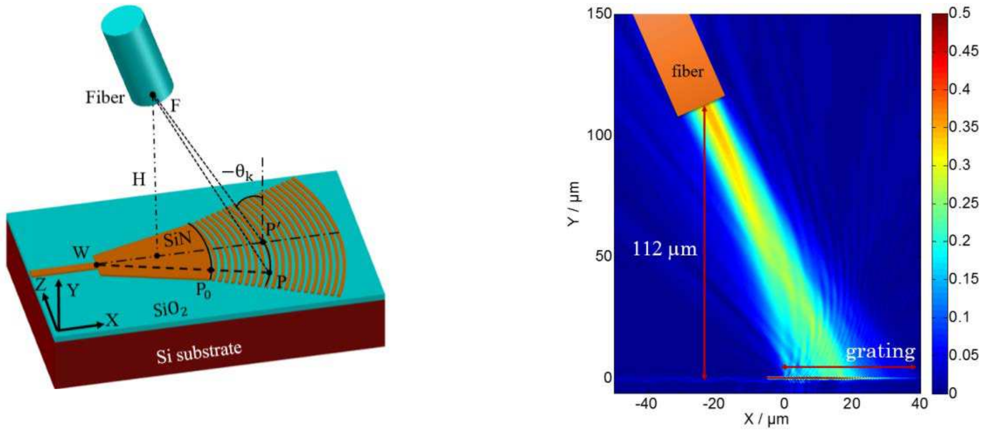
Figure 2: (a) 2D schematics of a zero-order grating coupler for the SOI platform; (b) Coupling efficiency as a function of the wavelength for the designed zero-order grating coupler.

In our proposed zero-order grating coupler, we substitute the radiating grating with a subwavelength grating (SWG) waveguide [4], so that all diffraction orders $|m| \geq 0$ are automatically frustrated. To allow radiation with the zeroth order (m = 0), a prism with $n_u > n_B$ is utilized. In this case, Eq. (1) becomes

$$n_u \sin(\theta) = n_B. \tag{2}$$

Now the wavelength dependence only comes from the modal and material dispersions of the structure, thus substantially increasing the bandwidth. Additionally, to achieve sub-decibel coupling efficiencies, we tilt the prism with an angle θ_{clad}, as shown in Fig. 2a. As indicated in [11], wedge-shaped claddings can lead to coupling efficiencies up to 95%.

We design a zero-order grating coupler at $\lambda = 1.55$ µm for the SOI platform [12]. The common minimum feature size of 100 nm imposes $\Lambda = 200$ nm and $DC = 50\%$. With these values, $\theta_{clad} = 1°$ and $L = 20.3$ µm yield optimum performance. Figure 2b shows the coupling efficiency as a function of the wavelength when the radiated light is collected by a SMF-28 optical fiber. A maximum coupling efficiency of 91% and a 1-dB bandwidth of 126 nm are reported. In this design, all power is radiated upwards and back-reflections of 3.3% are only due to the air-fiber index mismatch.



a) b)

Figure 3: a) Schematic geometry of the proposed self-imaging fiber-chip grating coupler; b) 2D FDTD simulation of the focusing beam radiated from chip surface.

4. CHIP-FIBER SELF-IMAGING GRATING COUPLER FOR SiN PLATFORM

SiN on SiO_2 technology is being actively explored for sensing and communications as it offers a wide range of wavelengths and high non-linearity. When designing surface grating couplers for this technology one of the problems is that radiation strength is very low which produces couplers that are too long for direct fiber coupling. Following the basic principles in [13], we propose a solution to this problem based on a self-imaging grating coupler [14]. By adjusting the amplitude and phase apodization along the length of the grating and simultaneously designing the curvature of the grating teeth, a focusing beam is radiated from the chip surface towards the fiber input aperture. In this way, the grating length can be substantially larger than the fiber mode diameter but still a high coupling efficiency can be attained. Figure 3a shows the schematics of the proposed self-imaging fiber-to-chip grating coupler, where it can be seen that the fiber is positioned at the focal point of the converging beam, which is far from the chip surface ($H \approx 112$ µm). The original 26.5 µm mode field diameter (MFD) Gaussian beam radiated from the chip surface is focused into the fiber Gaussian like mode (10.4 µm MFD) with a very good coupling efficiency of 86% (0.66 dB coupling loss). Figure 3b shows a 2D FDTD simulation of the focusing beam radiated from the surface of the chip. Preliminary experimental recently obtained validate the simulated results: -3 dB total insertion losses have been measured that, still being far from the designed values, are comparable with existing solutions for this platform.

5. CONCLUSIONS

New design techniques based in SWG structures and novel structures based in imaging concepts have enabled the design of key integrated optic devices with improved performance in terms of wavelength coverage and efficiency. An ultra-bandwidth SWG-based MMI has been designed in SOI exhibiting a measured operational bandwidth in excess of 300 nm at telecom wavelengths clearly exceeding the state of the art. Also, by means of a SWG structure a surface grating coupler has been designed for the same platform which, using the zero diffraction order attains a simulated 1 dB bandwidth of 126 nm. Finally, a self-imaging grating coupler has been designed for the SiN platform which has shown potential for sub-decibel efficiency.

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