Silicon sub-wavelength structures for refractive index and dispersion engineering

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We show that using sub-wavelength structures both refractive index and dispersion can be locally engineered in integrated silicon photonic waveguides. These concepts are exploited to enhance of the coupling efficiency of fiber-to-chip grating couplers by more than 3dB without increasing fabrication complexity, and to achieve a five-fold broadening of the bandwidth of directional couplers.

Silicon nano-photonics is becoming a platform of mayor interest in both research and industry, because it enables the fabrication of photonic devices with the same infrastructure used to mass-produce CMOS electronics and microprocessors. In fact, it is considered an ideal candidate for optical interconnects that will overcome the copper-wire bandwidth limitation in next generation computing systems [1]. The high precision with which silicon photonic structure can be fabricated enables the use waveguides consisting of a periodic array of two media with a sub-wavelength period. As predicted more than half a century ago such structures should completely suppress diffraction and exhibit an effective refractive index lying between the refractive indices of the two media [2]. Recently such sub-wavelength grating (SWG) waveguides consisting of segments of silicon and air arrayed along the direction of light propagation (see Fig. 1) were experimentally shown to indeed exhibit these characteristics [3]. In the following we describe how SWGs can be exploited for refractive engineering in fiber-to-chip grating couplers and dispersion engineering in directional couplers.

Fiber-to-chip grating couplers are fundamental devices for efficient light injection and extraction from silicon photonic chips. As shown schematically in Fig. 2(a) they operate by placing an optical fiber over the chip and using a grating to change the direction of propagation of light into the horizontally oriented waveguide. If the grating is defined with the same full etch as the waveguide, it becomes very strong and the overlap between the fiber mode and the grating field is poor, limiting coupling efficiency to about -7.7dB, as shown in Fig. 2(b) [4]. However, an SWG arrayed perpendicular to the direction of propagation in the grating grooves [shown in red in Fig. 2(a)], acts as an artificial medium with an intermediate refractive index controlled by the duty-cycle of the SWG [referring to Fig. 1 the duty-cycle of these structures is defined as DC=a/(Λ-a)]. This allows for a better control of the grating strength which results in a more than 3dB enhancement in coupling efficiency, as seen from the measurements in Fig. 2(b). By apodizing the duty-cycle of the SWG, as shown in Fig. 2(c), a further improvement in coupling efficiency as achieved as seen in Fig. 2(b) [5].

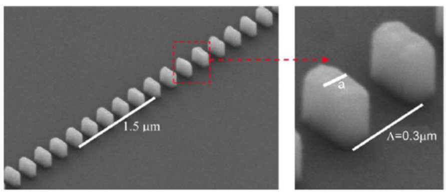

Figure 1: SEM image of a sub-wavelength waveguide, with a blowup of two segments.

Directional couplers are widely used devices in integrated optics, but their bandwidth is limited to around 20nm. As we showed in [6] this limitation arises from the wavelength dependence of the beat length of the coupler's two supermodes, labelled ϕ_1 and ϕ_2 in Fig. 3(a). We insert an SWG arrayed along the direction of propagation in the coupling region as highlighted in red in Fig. 3(a). By adequately designing the pitch this SWG and making use of the fact that its effective refractive index increases significantly as the Bragg wavelength is approached, the wavelength dependence of the beat length can be cancelled. 3D FDTD simulations show that this method flattens the insertion losses of the device over a bandwidth of almost 100nm, yielding fivefold bandwidth broadening compared to a coupler without SWG.

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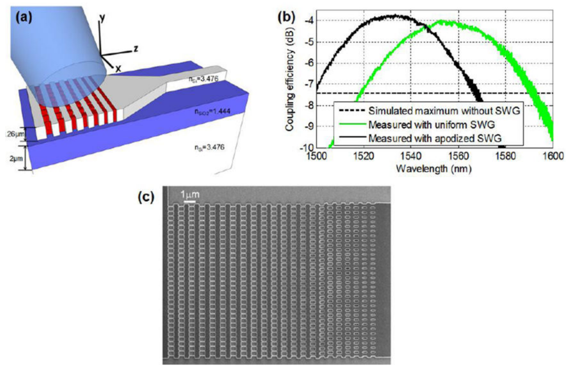

Figure 2: (a) Schematic of a fibre-to-chip grating coupler. (b) Coupling efficiencies of different gratings as a function of wavelength. (c) SEM image of an apodized fibre-to-chip grating coupler.

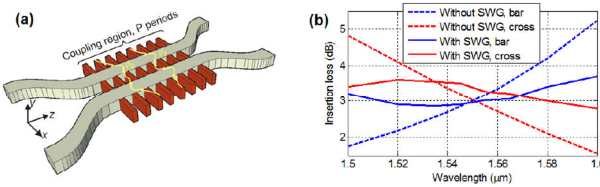

Figure 3: (a) Schematic of a SWG directional coupler. (b) Simulated insertion losses of a conventional coupler and a SWG directional coupler as a function of wavelength.