Ultra-broadband Silicon Photonic Multimode Interference Coupler

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In integrated optics, multimode interference couplers (MMIs) are used as light-wave splitters and combiners in a wide variety of devices ranging from spectrometers to sensors and coherent optical receivers. While their design and operation is generally well understood [1], the operational bandwidth remains limited. Here we present a sub-wavelength structured MMI, shown in Fig. 1(a), that overcomes this limitation and experimentally demonstrate a bandwidth exceeding 300nm at telecom wavelength, with more than 500nm bandwidth potentially attainable (as per 3D-FDTD simulations).

Referring to Fig. 1(b), in a MMI a light-wave with mode profile f_{in} is launched into the multimode region, exciting several higher order modes φ_i. These modes propagate with different phase constants β_i forming images of the input field f_{in}. A two-fold image is formed at the position $z = (3/2)\,L_\pi$, with $L_\pi = \pi/(\beta_1 - \beta_2)$ the beat-length of the two lowest order modes. By placing the output waveguides at this position a 3 dB coupler is obtained. However, the beat-length L_π is wavelength dependent, so the position of the images moves as wavelength is tuned, limiting the device bandwidth [1].

We use a sub-wavelength grating (SWG) metamaterial to overcome this limitation. SWGs behave as equivalent homogenous media with controllable refractive index, and have found widespread application in silicon photonics [2]-[5]. Broadband 3 dB couplers based on SWG directional couplers [6]-[7] and SWG adiabatic couplers [8] have been recently demonstrated, with bandwidths between 100 nm and 130 nm. In our SWG MMI [Fig. 1(a)], we exploit the anisotropy of the SWG to experimentally demonstrate a 3 dB coupler that covers 300nm of bandwidth around a wavelength of 1.55 µm. 3D FDTD simulations show that more than 500nm can be achieved.

The anisotropy of the SWG medium is analogous to that of a uniaxial crystal: two waves polarized along the x axis (electric field parallel to the silicon segments) and z axis (electric field perpendicular to the silicon segments) experience different equivalent indexes, n_{xx} and n_{zz} [Fig. 1(a)]. The device can thus be modelled as a conventional MMI composed of a homogenous anisotropic material [Fig. 1(b)]. The beat length of such an anisotropic MMI is given by $L_\pi \approx (4\mathrm{W}^2)/3\lambda \cdot n_{zz}^2/n_{xx}$, and is significantly shorter and less wavelength dependent compared to a conventional MMI [9].

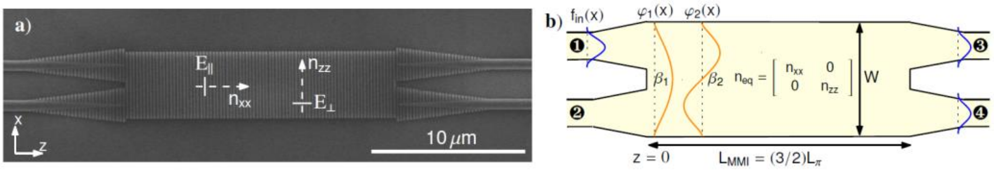

Fig. 1. (a) Scanning electron microscope image of a sub-wavelength patterned multimode interference coupler engineered for ultra-broadband operation. (b) Schematic top view of a 2×2 multimode interference coupler.

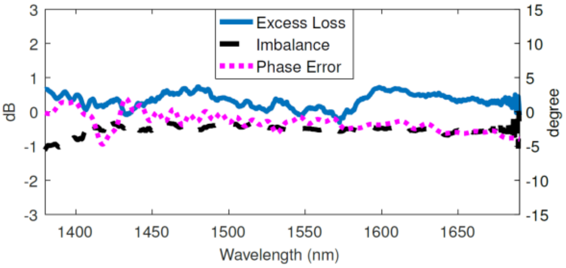

Fig. 2. Measured performance of the device shown in Fig. 1(a), revealing high-performance operation over a bandwidth in excess of 300nm, actually limited by the setup wavelength scanning range.

Figure 2 shows the performance of the sub-wavelength patterned MMI, measured using a broadband source and an optical spectrum analyser. Both imbalance (power difference between the two outputs) and excess loss (power lost in the device) are below 1 dB over the full measurement range (1380nm – 1700nm). The phase error (deviation from the ideal 90° phase shift between the outputs) is smaller than 5°. Even an ideal (simulated) conventional MMI device only exhibits a comparable performance over a limited bandwidth of 200nm.

We believe that such ultra-broadband MMI devices will pave the way towards broadband on-chip systems for diverse applications ranging from optical sensing to data communications.

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