Sci. Bull.
DOI 10.1007/s11434-016-1077-z

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Review

Physics & Astronomy

Subwavelength grating devices in silicon photonics

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Received: 22 January 2016 / Revised: 18 March 2016 / Accepted: 13 April 2016

Abstract Subwavelength grating (SWG) waveguides in silicon-on-insulator are emerging as an enabling technology for implementing compact, high-performance photonic integrated devices and circuits for signal processing and sensing applications. We provide an overview of our recent work on developing wavelength selective SWG waveguide filters based on Bragg gratings and ring resonators, as well as optical delay lines. These components increase the SWG waveguide component toolbox and can be used to realize more complex photonic integrated circuits with enhanced or new functionality.

Keywords Subwavelength gratings · Silicon photonics · Integrated optics · Bragg gratings · Ring resonators · Optical delay lines

1 Introduction

There is a growing need to develop integrated components for optical sensing and to perform a variety of signal processing functions in broadband (optical and microwave photonics) communications. Over the past few years, the development of active and passive devices in silicon photonics has been the subject of intense research and a number of enabling technologies have been demonstrated [1].

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While the principles of subwavelength grating (SWG) structures have been long known, it has only been in the past few years that they have attracted interest for developing integrated optical components [2, 3]. Early research focused on crosswise operation where light propagates orthogonally to the subwavelength structure and various silicon-on-insulator (SOI)-based devices and applications were reported, most notably, efficient fiber-to-chip surface grating couplers [4, 5].

Recently, it was shown that light can propagate lengthwise in the subwavelength structure and be guided, in the same way as in a conventional waveguide. This observation gave rise to so-called microphotonic SWG waveguides [6]. In theory, such waveguides are lossless whereas in practice, a loss as low as 2.1 dB/cm was obtained for an SWG waveguide in SOI. SWG waveguides have enabled a whole new platform in silicon photonics and indeed, a variety of devices have been proposed and demonstrated, including low loss (<1 dB) SWG tapers for coupling efficiently SWG waveguide devices to conventional silicon strip waveguides; SWG directional couplers with over 40 nm bandwidth and compact multimode interference couplers [7]; SWG waveguide crossings with negligible losses and waveguide bends with a loss as low as 0.8 dB per 90° bend [8, 9]; mode transformers for butt coupling and mode conversion [10]; and polarization converters [11]. All of these devices, with the exception of the polarization converter, can be fabricated with a single etch process. Moreover, they are compatible with one another and can be used to create more complex integrated devices, subsystems, and optical links. However, one fundamental building block that is missing in the SWG waveguide component toolbox is a wavelength selective filter.

In this paper, we review recent work on developing wavelength selective SWG waveguide devices based on

Bragg gratings (BGs) [12, 13] and ring resonators [12, 14, 15], as well as optical delay lines (ODLs) [16]. The SWG BG and ring resonator filters can be used to develop more advanced wavelength selective components, such as optical add-drop multiplexers. The SWG ODLs can be used to implement the waveguide array in arrayed waveguide gratings and can also have important applications in optical communications and microwave photonic systems, such as to provide synchronization for all-optical signal processing or broadband phase-shifting for phase array antennas and beamforming.

2 Background

SWGs are grating structures with a period Λ that is sufficiently small compared to the wavelength of light. They are formed by a periodic arrangement (with period Λ) of high refractive index material with a thickness a implanted into a low refractive index material (the duty cycle of the SWG is defined as $D = a/\Lambda$). To create an SWG waveguide, finite transverse dimensions (e.g., a width W and height h) are applied to the material of high refractive index. Light propagation in the direction along the periodic refractive index arrangement (i.e., lengthwise operation) is similar to electron propagation in a periodic potential and can be described using Bloch waves. The carrier frequency of the light signal propagating in the SWG determines the operating regime. At low frequencies, the propagation constant (k_B) increases with frequency in a similar manner to a conventional waveguide, i.e., the subwavelength regime. Once the frequency increases to the photonic bandgap, Bragg reflection occurs and light is reflected back, i.e., the Bragg reflection regime. Above the first bandgap is the radiation regime where the Bloch mode becomes leaky and light is scattered out of the waveguide, i.e., the radiation regime. We are particularly interested in the subwavelength regime where the propagating light perceives the periodic structure as an effective medium. In other words, the SWG waveguide can be modeled as a conventional strip waveguide having the same transverse dimensions and a uniform refractive (effective) index along the direction of propagation. The effective index of the waveguide depends on the duty cycle [6, 17, 18].

SWG waveguides in SOI can be realized by a periodic arrangement of silicon and silica as shown schematically in Fig. 1a. For fabrication processes available from typical silicon photonic multi-project wafer runs, $h = 220$ nm and the silicon layer sits on top of a 3 μm buried-oxide (BOX) layer; it is covered by a 2 μm cladding that is index-matched to the BOX layer, see Fig. 1b. The SWG waveguides considered throughout this paper also include an input and an output SWG taper. The taper serves to convert a

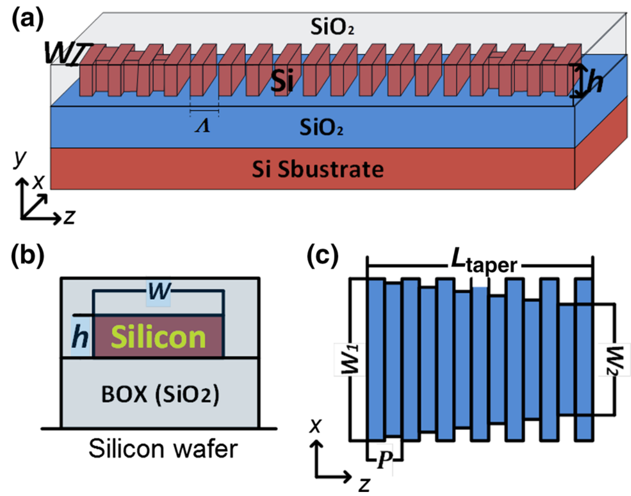

Fig. 1 (Color online) **a** SWG waveguide implemented in SOI, **b** cross-section of the waveguide, and **c** top view of the SWG taper

conventional waveguide mode propagating in a silicon strip waveguide into a Bloch mode that propagates in the SWG waveguide. The taper is based on a linearly chirped waveguide grating implemented with a uniform period P and where the waveguide width is narrowed linearly from W_1 to W_2 over a length L_{taper}, see Fig. 1c [8]. Figure 2 shows the E-field propagating in a strip waveguide and an SWG waveguide in SOI calculated using a 2.5D FDTD simulator (Lumerical^{TM}). The waveguides have the same cross-section of $W = 500$ nm $\times$ $h = 220$ nm, and the SWG waveguide has a period $\Lambda = 300$ nm and $D = 50$ %. We can clearly observe the difference between the TE-like

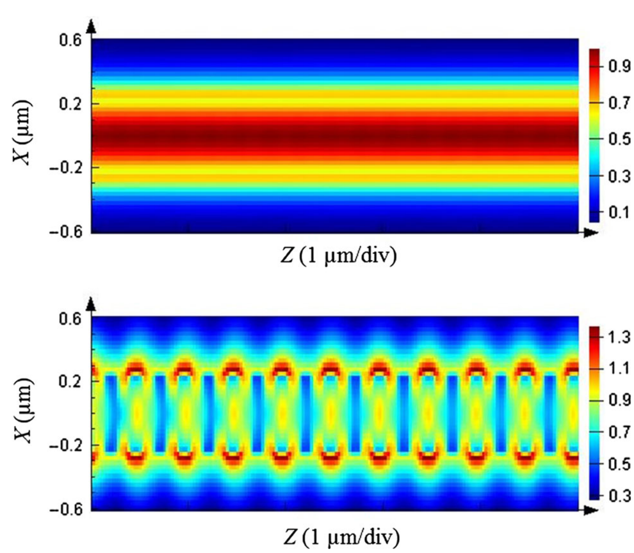

Fig. 2 (Color online) Comparing the E-field profile for a TE-like mode propagating in a strip waveguide and a Bloch mode propagating in an SWG waveguide in SOI (the waveguides have the same cross-section)