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Review

A hollow waveguide Bragg reflector: A tunable platform for integrated photonics

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ABSTRACT

Hollow waveguides are promising candidates for applications in sensing and high-power transmission. Flexible design and cost effective fabrication of hollow waveguides make it possible to realize integrated devices with small temperature dependence, tight control on optical confinement and tailorable characteristics. One of the potential applications of hollow waveguide is a tunable Bragg reflector, which can be used as building block for integrated photonics. In this review, integrated tunable Bragg reflector based on hollow-core optical waveguide is reviewed and presented; this Bragg reflector offers variable characteristics and design flexibility for applications in reconfigurable integrated photonic devices and circuits. Variety of tunable optical functions can be realized with on-chip Bragg reflector based on hollow waveguide, few of them are discussed in this review. Ultra-wide tuning in Bragg wavelength and on-chip polarization control can be realized using 3D hollow waveguide. A tapered 3D hollow waveguide Bragg reflector for an adjustable compensation of polarization mode dispersion (PMD) is then discussed. The utilization of a high-index contrast grating in hollow waveguide is demonstrated to reduce the polarization dependence and reflection-bandwidth. The polarization- and bandwidth control may be useful for realizing polarization insensitive devices and semiconductor lasers with ultra-wide tuning.

Contents

1. Introduction

Wavelength division multiplexing (WDM) is most deployed technology to fulfill the increasing bandwidth demand [1,2]. Tunable optical devices have proven their potential in optical communication systems [3]. By adding wavelength as an additional degree of freedom for routing and switching, it could be possible to architect new cost-effective reconfigurable all-optical switching systems with less congestion. That was an exciting application for tunable lasers [4–7] which may utilize smart resonator structures made up of some tunable waveguide. It has always been attractive to use hollow waveguides (HWGs) for variety of applications including on-chip sensing [8,9]. The novel concepts for guiding light in a waveguide of a core of refractive index lower than that of cladding were proposed in the form of Bragg fibers [10], Omni waveguides [11] and antiresonant

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reflecting optical waveguides (ARROW) [12]. Usually, optical guiding is accomplished by confining light to a region with high refractive index surrounded by cladding material with lower refractive index. Waveguide with an air core offers the potential to minimize the dependence of light transmission on air core transparency, thus various hollow waveguide structures have been studied extensively [13–19].

The hollow core waveguides have a lot of advantages including low nonlinearity, low optical damage threshold and strong optical confinement [20–24]. Thus, there are various applications such as high power lasers/optical guiding, precise micromachining and gas/liquid sensing. Attenuation and nonlinearities resulting from the interaction of light with the dense, material-filled core in conventional dielectric waveguides can be circumvented by confining light in an air core using highly reflective walls [20–27]. Interestingly, integrated hollow waveguide makes it possible to realize temperature insensitive and widely tunable photonic devices for reconfigurable photonic networks [24–30] where giant tuning in propagation characteristics can be achieved by a variable air core using micro-electro-mechanical system (MEMS) actuator. External reflectors including Bragg reflectors are important optical elements for adding extra functionalities into photonic devices. Hollow waveguides can be used to make Bragg reflectors [31–33]. Owing to the features from HWG, integrated devices with wide tuning range and athermal operation can be realized with HWG which can include in-plane laser with simple tuning scheme with a variable air-core HWG made up of two identical mirrors of dielectric multilayer distributed Bragg reflector (DBRs) [31]. A Bragg reflector based on a grating loaded hollow waveguide can be used to make a single frequency in-plane laser by integrating it with a semiconductor optical amplifier (SOA) [33–35]. The Bragg reflector based on hollow waveguide can be a building block for making tunable integrated photonic devices e.g. tunable filter, tunable resonator and so on [36–38]. In this review, physics, technology and special features of tunable Bragg reflector based on integrated hollow waveguides are presented; the hollow waveguide is shown to have the capability of tailoring the characteristics of on-chip optical devices. The possibility of two-dimensional (2D) optical confinement, an important requirement for compact optical devices, is also discussed by converting the hollow structure into a 3D hollow waveguide. The salient features of 3D hollow waveguide are elaborated. Design and fabrication of the tunable Bragg reflector based on 3D hollow waveguide are discussed with successful demonstration of tuning function for various applications.

2. Optical confinement in hollow waveguides

Fiber Bragg waveguides are known for guiding the confined modes in the low index core which is surrounded by alternating cladding of high and low refractive indices such that the index of the core is equal to or lower than the index of lower index cladding layer. The transmission losses are very low due to the Bloch wave band-gaps produced by binary layered cladding and the modes guided in the core sustain only for wavelengths and propagation constants that lies within the Bloch modes' band-gaps [10]. The spectral properties of band-gaps are dependent upon incident angle and refractive index of the incident medium. Similar type of planar waveguide is ARROW, in which light is confined by the cladding layers which are designed to form anti-resonant Fabry–Perot cavities [12]. Each cladding layer guides the light at its resonant frequency. Even though the ARROW mode is leaky, the radiation losses can be minimized by the high reflectivity provided by the anti-resonant claddings.

Another type of waveguides are slot waveguides which have the capability to guide and confine light in such a way that very high optical intensity is acquired in a small cross-sectional area [23] having sufficiently low refractive index, relative to the remaining part of the structure. The high optical intensity in the gap is achieved because of the discontinuity of electric field at the high index contrast interfaces. This distinctive characteristic makes the slot-waveguide a prime candidate for numerous applications, including *Nanophotonics* especially for light-on-chip circuits. In contrary, Bragg reflector waveguides (BRW) guide light in any refractive index region by utilizing the stop-band of a transverse distributed Bragg reflector [10,15]. In order to obtain zero loss, large numbers of cladding periods are required [14]. These support the nonlinear guided modes for nonlinear propagation at high optical power. The distinctive properties of BRW are used to fabricate polarization combiners/splitters.

3. Tunable planar hollow optical waveguide

One of the major advantages of hollow core waveguides is their temperature insensitivity. For many applications in optical fiber communications and sensing, the sensitivity of the phase delay of optical guided mode to temperature is critical and it would be advantageous to decrease this sensitivity. In hollow waveguides, the guided mode is almost entirely confined to the air core region, whereas in a conventional waveguide it is entirely contained in solid materials. Since the refractive index of air depends much less on temperature than the refractive index of solid materials, the phase delay is expected to have a much lower dependence on temperature in hollow waveguides than in conventional waveguides. It has been difficult to utilize the conventional tuning schemes such as thermo-optic or electro-optic effects in hollow waveguides with an air core. Thus, applications to tunable optical devices were hardly discussed at all. In 2001, a novel tunable hollow waveguide structure with variable air core for tunable optical device applications was proposed by Miura and Koyama [24]. The combination of both hollow waveguides and MEMS actuators adds a tuning function to hollow waveguides. Tunable hollow waveguides consist of two highly reflective multilayer mirrors, called distributed Bragg reflectors (DBR). The DBR mirrors can efficiently confine the light in an air core sandwiched between them. The DBR mirrors with MEMS actuator driven by electrostatic force or thermal bimorph stress bring dynamic mechanical displacement of an air core. The schematic of the tunable hollow waveguide with a variable air core thickness with MEMS is shown in Fig. 1.

The propagation characteristics of hollow waveguide are strongly dependent on air-core dimension; thus one can achieve wide tuning operation of optical properties by air-core dimension control. One-dimensional and two-dimensional optical confinements have been proposed and demonstrated with tunable hollow waveguide structures based on this concept using slab and 3D hollow waveguides, respectively as shown in Fig. 2(a) and (b). In slab hollow waveguides, vertical confinement (1D) of light is achieved by Bragg reflections due to multilayer (DBR) cladding. To obtain 2D confinement (vertical as well as lateral) a 3D structure

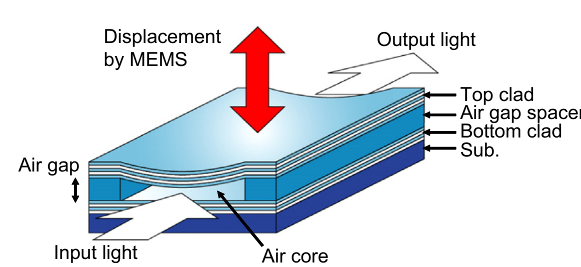

Fig. 1. Schematic of a tunable hollow optical waveguide with MEMS.