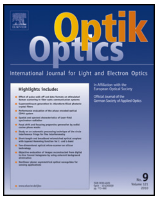
Optik 127 (2016) 1260–1264

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Slow light photonic crystal waveguide with large quality factor

Nagesh Janrao[a,*], Vijay Janyani[b]

[a] Department of Electronics & Communication Engineering, Government Polytechnic, Shiwaji Nagar, Pune, India
[b] Department of Electronics & Communication Engineering, Malaviya National Institute of Technology, Malviya Nagar, JLN Marg, Jaipur, Rajasthan 302017, India

ARTICLE INFO

Article history:
Received 31 March 2015
Accepted 4 November 2015

Keywords:
Photonic crystal waveguides
Slow light
Quality factor
Normalized delay-bandwidth product

ABSTRACT

Optical cavities have been used in wavelength-division-multiplexing systems as well as they are useful for sensing applications. Optical cavity trap light for a single resonant frequency. There are low losses in high quality factor optical cavities. In present work we analyzed photonic crystal cavities that having extremely high value quality factor and normalized delay-bandwidth product calculated for the cavity based waveguides.

1. Introduction

The twenty first century is the era of data and information technology. Photonic crystals have generated increasing interest in optical field due to the band-gap property. Hence modern optical telecommunication systems are now start utilizing more and more on photonic crystals in order to achieve miniature, tunable and functional devices which can perform various functions such as dynamic routing and switching, wave guiding, signal processing and filtering. Normally photonic crystals are used along with optical fibers [1–8]. Therefore photonic crystals are opening up the field to a wide-range of new and exciting applications that have the significant impact on the variety of technologies [6–21]. Dispersion compensation and slow light propagation with help of photonic crystal plays a significant role in optical communication. Applications based on photonic crystals generally use the dispersion relation of modes provided by dielectric properties of material used for making of photonic crystals (PhC) and geometry of photonic crystal structures. The dispersion relationship having nearly zero slope close to the band edge of Brillouin zone (BZ) that results in slow light mode. Slow light can result in significant improvement of interaction between the dielectric material and the electromagnetic field and hence nonlinear properties are enhanced. Moreover, in devices such as the directional coupler, by providing a slow-light region, the length of directional couplers can be reduced to few micrometers. The most important parameter to quantify the performance of slow light is the 'Normalized delay-bandwidth product' (NDBP) [11]. NDBP is the product of average group index n_g and frequency range (bandwidth) over which n_g remains nearly constant. To be best of our, knowledge this is the first time NDBP calculated for the cavity based waveguides.

2. Guiding mechanism in photonic crystal waveguides and slow light

When dielectric defect is created in the crystal two guiding mechanisms coexist to confine the light in the lateral direction within the waveguide. They are classified as

(i) Index guiding
(ii) Photonic band-gap guiding.

Index guiding mechanism of photonic crystal waveguides is based on the total internal reflection of light at the interface between a high and low index medium. In rod type photonic crystal waveguide light is propagating through lower refractive index medium surrounded by high index rods. In hole type photonic crystal waveguide light is propagating through high refractive index medium surrounded by air holes or low index holes. These two mediums are also known as core and cladding of the photonic crystal waveguide respectively. An index guided mode has high energy concentrated inside defect. It interacts only with the first row of holes adjacent to the channel or defect. Index guided modes exists below the projected band of bulk photonic crystal and within

---

* Corresponding author. Tel.: +91 9352327287.
E-mail address: janraonl@yahoo.com (N. Janrao).

http://dx.doi.org/10.1016/j.ijleo.2015.11.015

the band-gap region also. Unlike index guided modes, gap guided modes only exists within the band-gap region of crystal [22,23]. A band-gap guided mode interact with more than one row of holes adjacent to the defect but high concentration of energy is found to be in first and second row of the holes near the defect. Index guiding and photonic band-gap guiding coexist and their combined effect defines the shape of guided mode within waveguide [22–24]. Propagating mode in cavities based slow light photonic crystal waveguides is a band-gap guided mode. Cavities based slow light photonic crystal waveguides analyzed in this paper enhance the electric field at the expense of bandwidth. Bandwidth of such cavities based slow light photonic crystal waveguides is low hence nonlinear properties also feeble. But for some applications such as optical switching, multiplexing/demultiplexing in optical networks low bandwidth slow lights are useful. Some parameters useful for characterizing the slow light waveguide system are discussed here; the definition of these parameters is as follows.

(i) The group velocity: The group velocity of a guided mode is calculated, by its definition as the derivative of the angular frequency over the wave vector ($v_g = \partial\omega/\partial k$)

(ii) Group index: $n_g = c/v_g$, where c is speed of light in free space.

(iii) Group velocity dispersion (β_2) is second derivative of the wave vector (k) with respect to angular frequency (ω), Group velocity dispersion (β_2) is given by [25]

$$\beta_2 = \frac{\partial^2 k}{\partial\omega^2} \tag{1}$$

whereas GVD parameter is given as [26]

$$GVD = -\frac{2\pi}{\lambda^2}\beta_2 = \frac{2\pi c}{\lambda^2}\frac{\partial^2 k}{\partial\omega^2} \tag{2}$$

(iv) Normalized delay-bandwidth product (NDBP)

(v) The most important parameter to quantify the performance of slow light is 'Normalized delay-bandwidth product' (NDBP). It is used to define the capacity of the slow light device [27]. (NDBP) is the product of average group index n_g and frequency range (bandwidth) over which n_g remains nearly constant. NDBP is given as

$$NDBP = n_g \times \left[\frac{\Delta\omega}{\omega_0}\right] \tag{3}$$

where ($\Delta\omega/\omega_0$) is normalized bandwidth. The group index is assumed constant within ±10% variation of average group index n_g. By changing dimensions of the structure, operating wavelength is changed so that design of slow light waveguide is more flexible. The slow down factor S has been defined as the ratio of phase velocity over group velocity [27], hence $S = v_p/v_g$, where S = slowdown factor, v_p = phase velocity and v_g = group velocity.

There are certain advantages of slow light like, slow light structure offer more bandwidth that means broader wavelength range of operations. By changing dimensions of the structure operating wavelength is changed so that design of slow light waveguide is more flexible [27,28]. Disadvantage of slow light photonic crystals waveguide is that it is very difficult to tune the slowdown factor [27].

3. Simulation results and discussion

Slow light and high quality factor makes photonic-crystal cavities ideal for integrated optical devices. Normally quality factor increases exponentially with the number of crystal periods that surround the defect [28]. The quality factor Q is a measure of the losses in the cavity [28]. Quality factor (Q) is defined as

$$Q = \frac{\textit{stored energy}}{\textit{Power loss per cycle}} = \frac{\omega_0}{\Delta\omega}$$

where $\Delta\omega$ is the full-width at half-maximum (FWHM).

The proposed structure for high value quality factor is as shown in Fig. 1. Structure is composed of a photonic crystal waveguides (PCW) and coupled cavities such that cavities are placed at center of waveguide with a new periodicity of $a' = 3a$, where a is the lattice constant. The structure is based on a 2D PC formed by a square lattice with, the radius $R = 0.25a$ and refractive index of rod is 3.4. With these parameters, but no defect a band gap for TE modes (with convection shown in Fig. 1) has been found in the spectral range $0.26 \le a/\lambda \le 0.36$. The guided mode through this kind of coupled cavity waveguide can be controlled by changing the radius of the point defect. Radius of point defect is equal to 'dr' as shown in the Fig. 1.

Dispersion relations for the modes guided by the coupled cavities photonic crystal waveguide are shown in Fig. 2. The dispersion curves were evaluated by plane-wave expansion method. These guided modes inside the band gap are analyzed by super cell method [29,30]. Super cell (7 × 3) has been shown by dotted lines in Fig. 1. These dispersion relations are obtained for different values of point defect (dr). For deficit dr equal to 0.08 μm propagating mode is in the range of normalized frequency from 0.32774 to 0.32792. Similarly with values of dr equal to 0.10 μm, 0.12 μm, 0.14 μm, the propagating modes are in the range of normalized frequencies between 0.31306 to 0.31321, 0.29714 to 0.29726 and 0.28206 to 0.28318 respectively. The propagating mode shifts upwards when point radius is reduced.

Decreasing radius dr of point defect, reduces refractive index material in ΓK direction center to WG, therefore guided modes are pulled upwards. The performance of slow light device is measured by calculating the variation of group index for each guided modes. In Fig. 3, group index n_g is plotted against normalized frequency for decreasing point defect radius dr. It is seen that this photonic devices generate extremely large group index. In slow light devices average group index n_g is decreases with the corresponding increase in bandwidth. This shows the trade-off between group index and bandwidth [31]. Table 1 summarizes the average group index, bandwidth; NDBP for different point defect radius (dr). From Table 1, it has been observed that the trade-off between group

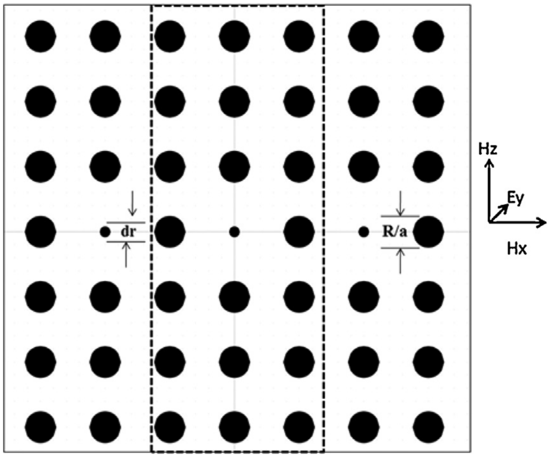


Fig. 1. Photonic crystal waveguides (PCW) and coupled cavities made using a square lattice. Radius of bulk structure is $R = 0.25a$. The cavities are placed at center of waveguide with a new periodicity of $a' = 3a$ with radius of point defect is equals to 'dr'. Super cell (7 × 3) are shown by dotted lines.