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Design of tunable filter by Kerr effect used in optical communications

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The discovery of photonic Band-gap (PBG) materials and their use in controlling light propagation is a new and exciting development. An optical design of a wavelength-selective tunable filter permitting to select a channel of 1 nm of spectral width among 40 channels situated between 1550 nm and 1590 nm is considered in this paper. Guided modes in a two dimensional dielectric photonic crystal (PC) waveguides are studied by the transfer matrix method (TMM) and Galerkin method. A cavity (localized defect) between two waveguides in the PC structure is introduced. Among several wavelengths circulating into the first guide, the resonance wavelength with the defect can be extracted by coupling effect, and then is injected into the second guide. The tuning effect is obtained by Kerr effect applied in the cavity.

INTRODUCTION

Photonic crystals, dielectric structures that make it possible to forbid the propagation of photons, are recognized able to provide effective control of light. Indeed, it is possible to produce guides with almost null side losses and devices of filtering [1].

Owing to the difficulties associated with the fabrication of three-dimensional (3D) photonic crystals, planar photonic crystals (PPC) [2] have attracted significant research attention. The basis of the PPC is a dielectric slab, perforated with a two dimensional (2D) periodic lattice of holes. Due to the periodicity of lattice, frequency bandgaps for guided modes of the slab are opened, and light of certain frequencies cannot propagate in the slab [3]. The light is localized to the slab in the vertical direction by means of total internal reflection and is controlled in the lateral direction by the 2D PC. The combination of these two mechanisms makes localization of light in all three dimensions possible.

In this report, we propose a wavelength tunable filter containing microcavity carried inside the 2D photonic crystal. The filter must be tunable on a range of 40 nm located between 1550 nm and 1590 nm, the full-width at half maximum (FWHM) is 1 nm. These characteristics are compatible with wavelength division multiplexing specifications of optical telecommunications [4].

1. DESIGN

The system that we consider is a selective filter, combining cavity and waveguides with photonic crystals [5, 6]. A cavity is a localized defect into the photonic structure, whereas a PC waveguide is produced by introducing a linear defect.

When two PC waveguides are brought in close proximity of each other, they form a directional coupler, shown in fig. 1. Under suitable conditions, an electromagnetic lightwave launched into one of the waveguides can couple completely into the nearby waveguide. Once the wave has crossed over, the wave couples back into the first guide so that the power is exchanged continuously as often as the length between the two waveguides permits. However, complete exchange of optical power is only possible between modes that have equal propagation constants. Equality of propagation constant occurs naturally when the two waveguides are identical. In that case, all the guided modes of both waveguides can couple to each other at all wavelengths [7, 8].

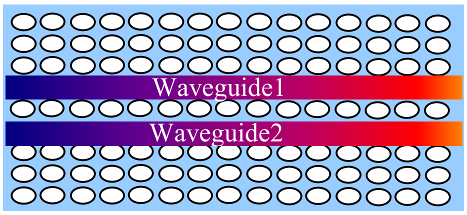

Fig. 1. Coupled photonic crystal waveguides

The structure of the filter (fig. 2) is made of a suspended membrane containing III-V semiconductor bored of air holes on InP substrate [9].

By applying the principle of the coupling already defined, the guidance of the light starting from the waveguide towards the cavity is obtained by coupling; the light is extracted from the cavity by a second waveguide [10, 11]. The structure is represented in fig. 2.

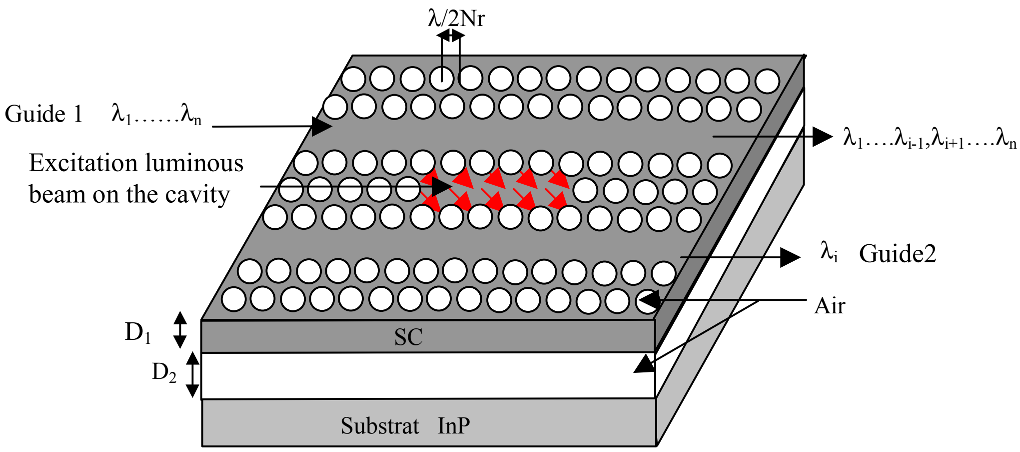

Fig. 2. General structure of a filter containing PC microcavity and coupled guides

If one injects into the cavity an electromagnetic mode, a micro-resonator is created. Knowing that the authorized frequencies modes depend on the cavity, and if we vary its index, we can reach any frequency located in the bandgap.

Among several wavelengths circulating into the first guide, the resonance wavelength with the cavity can be extracted by coupling effect, and then is injected into the second guide.

2. NUMERICAL ANALYZES

A variety of methods have been used to analysing photonic crystals. Among these there are plane wave expansion method [12], transfer matrix method [13, 14], finite difference method [15]

For simplicity and fasting reasons, the methods used in this study are the Galerkin method [16, 17], and transfer matrix method [TMM].

In Galerkin's method the propagating field is expressed as a series expansion in terms of a complete set of orthogonal allowing to determine the propagating characteristics and field distributions of the guided modes.

The transfer matrix method (TMM) uses the continuities conditions of the field, what makes it possible to obtain a transfer matrix of a medium to another. This matrix connects the amplitudes of the incident fields to the transmitted and reflected fields.

When the semi-conductor (SC) material is subjected to an excitation of very strong intensity I (by Kerr effect), the refraction index (Nc) becomes:

$$Nc = Nr + N_2 I, \tag{1}$$

where Nr is the linear refraction index, N_2 is the coefficient of nonlinearity.

Thus, the refraction index variation of the cavity will involve the displacement of resonance wavelength λ.

The cavity length H is given by

$$H = k\frac{\lambda}{2Nc}, \tag{2}$$

where k is the order of resonance, λ is the resonance wavelength.

We can determine the FWHM ($\Delta\lambda$):

$$\Delta\lambda = \frac{\lambda^2}{2\pi Nc\, H}\frac{1-R}{\sqrt{R}}, \tag{3}$$

where R is the reflection coefficient in the cavity.

3. APPLICATION

We are choosing AlGaAs with 18% of aluminium [18, 19], optimum alloy to manufacture components around 1550 nm into nonlinear integrated optics. Similarly the Kerr nonlinearity N_2 is $1.6\cdot10^{-13}$ cm^2/W which is an appreciable value. And thus $Nc = 3.2852 + 1.6\cdot10^{-13}$ I.

The semiconductor structure is composed by a guiding layer of AlGaAs with thickness D_1=0.27 µm, index Nr=3.2852 surrounded by Air. This structure is permitting to guide a single mode to the wavelength 1.55 µm.

By the Galerkin method the effective index of this waveguide is 2.767 for 1550 nm. The layout of the field in fig. 3 illustrates the vertical containment of the field in the guiding layer.

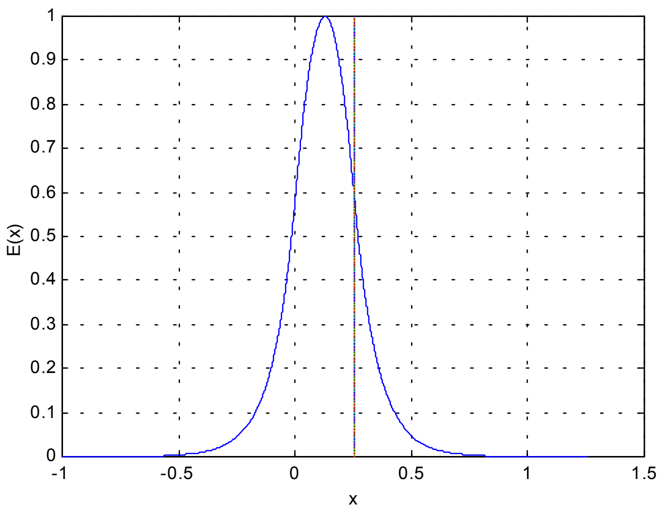

Fig. 3. Illustration of the vertical containment of the field in the guiding layer

One notices according to fig. 3, that the thickness D_2 (between SC and InP) should exceed 0.8 µm so that the field is cancelled.

Thus according to equation 2 the cavity length is H = 11.20 µm (21 holes to be omitted).

According to equation 3 the reflectivity R necessary to realise a selectivity $\Delta\lambda$ of 1 nm must be higher than 92%. And to reach a reflectivity superior to this value, the necessary holes number of Air is 2 holes on both sides of the cavity.

With 3 holes on both sides of the cavity, the reflectivity exceeds 99%.

In the following table, we present the refraction index (Nc) of the cavity, thus the necessary intensity to select certain wavelength of the tuning range of this filter, located between 1550 nm and 1590 nm.

λ (μm)	Nc	I (10^{11} W/cm^2)
1.55	3.28	0.0
1.56	3.31	1.875
1.57	3.33	3.125
1.58	3.35	4.375
1.59	3.37	5.625

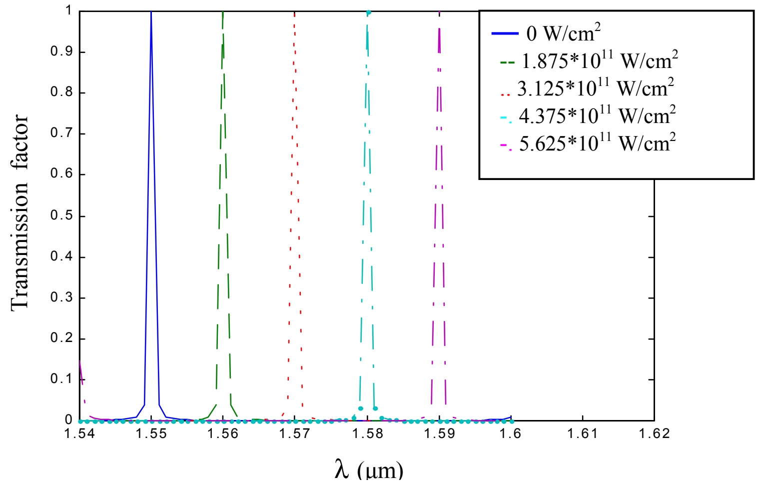

Fig. 4. The various transmissions spectra according to the wavelength

In fig. 4, we have the various transmissions spectra and the necessary intensity to select each wavelength of the range.

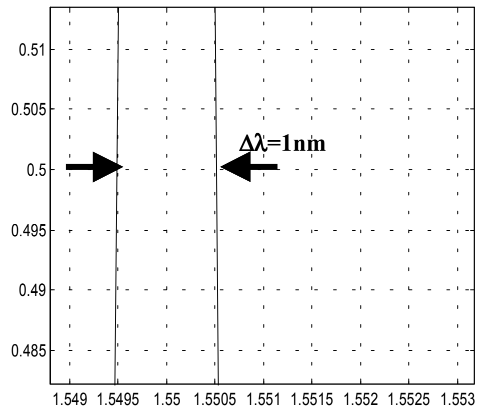

Fig. 5. FWHM at 1.55 μm

In fig. 5 we traced the FWHM of the peak selected at the wavelength 1.55 μm, the selectivity is Δλ = 1 nm. This is valid for any wavelength selected in the interval 1.55 μm to 1.59 μm.

4. CONCLUSION

The system that we conceived is a selective tunable filter combining PC cavity and waveguides in 2D.

The vertical containment of the wavelength is ensured by the index difference formed by (Air / $Ga_{0.82}Al_{0.18}As$ / Air), the lateral containment of the photons is obtained by 2D PC.

A localized defect coupled with the PC guides, constitutes the resonator cavity.

The Kerr effect generated in the cavity ($Ga_{0.82}Al_{0.18}As$), producing the tuning concept in wavelength on the range of 40 nm with a selectivity of 1 nm for an intensity of $6{\cdot}10^{11}$ W/cm^2, destined to the applications of WDM.

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