Optics Communications 365 (2016) 225–230

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Dispersion blue-shift in an aperiodic Bragg reflection waveguide

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ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
4 December 2015
Accepted 11 December 2015
Available online 18 December 2015

Keywords:
Photonic crystals
Bragg reflection waveguide
Aperiodic structure
Dispersion characteristics

ABSTRACT

A particular feature of an aperiodic design of cladding of Bragg reflection waveguides to demonstrate a dispersion blue-shift is elucidated. It is made on the basis of a comparative study of dispersion characteristics of both periodic and aperiodic configurations of Bragg mirrors in the waveguide system, wherein for the aperiodic configuration three procedures for layers alternating, namely Fibonacci, Thue–Morse and Kolakoski substitutional rules are considered. It was found out that, in a Bragg reflection waveguide with any considered aperiodic cladding, dispersion curves of guided modes appear to be shifted to shorter wavelengths compared to the periodic configuration regardless of the modes polarization.

1. Introduction

As is known, in contrast with conventional optical waveguides based on the effect of the total internal reflection inside a high-index core [1], distinctive features of Bragg reflection waveguides are influenced by a multilayered configuration of their composite cladding [2], which has a form of a stack of alternating high- and low-index layers. Indeed, such a composition of cladding leads to formation of photonic bandgaps in the spectra of the multilayered system resulting in light confinement within a low-index core which is usually considered to be an air gap. Such photonic bandgap guidance brings several attractive features to the waveguide characteristics [3,4], in particular, since most of light is guided inside a low-index core, losses and nonlinear effects can be significantly suppressed compared to the conventional high-index guiding waveguides.

Furthermore, even in the simplest symmetric configuration of Bragg reflection waveguides there is a set of unique optical features that are unattainable in conventional waveguides since the former ones are highly dispersive due to their complicate geometry (rather than just to their material composition). As such features we can mention that in Bragg reflection waveguides [5,6]: (i) each guided mode has several cutoff points, which results in ability to design a waveguide supported only the high-order modes instead of the fundamental one; (ii) there is a possibility to lose a specific mode due to shrinking of the photonic bandgap into point; (iii) some specific modes with negative order can appear when a system consists of a thin enough guiding layer. On the other hand, Bragg reflection waveguides exhibit an extra degree of freedom for optimizing their optical characteristics through utilization of particular designs of the cladding, among which an asymmetric mirrors design [7,8], layers chirping in the cladding [9,10], and placing the matched layers between the core and cladding [11] may be referred.

In this paper we report on the other possibility of tuning the operation bandwidth of Bragg reflection waveguides by applying an another special design to the multilayered cladding. Our motivation in this study is in follows. If we have a look from the viewpoint of practical applications, both the number of layers in the cladding and their thicknesses should be as small as possible. It is due to the fact that the production of waveguides with thinner layers requires fewer amount of materials for deposition, and thus less time for the process. At the same time, it contradicts with the technological limits that are imposed on the possibility of producing layers with a very small thicknesses. Besides, it is difficult to reach precise step-index profiles with sharp boundaries, and this problem is more significant for structures with the thinnest layers. In this context, it is of interest to find such a configuration of layers in the cladding, which would allow one to shift the operation frequency of the waveguide into the higher band without changing number of layers and their thicknesses.

It is obvious that through the solution of an optimization problem [12] it is possible to find the best spatial distribution of layers in a random sequence that produces a maximal shift, however, in this consideration we prefer to deal with deterministically ordered structures instead of completely random ones, since in the first case we are able to definitely predict the spectral properties of the system [13–17], i.e. the width and position of stopbands on the frequency scale, which are key characteristics that are taken into consideration when designing the Bragg reflection waveguides. As

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http://dx.doi.org/10.1016/j.optcom.2015.12.016
0030-4018/

noted in our previous papers [18–21], stopbands in the spectra of aperiodic structures can appear to be shifted in comparison with the stopbands in the spectra of periodic structures assuming the same material parameters and number of layers in the multilayered systems. Therefore, in this paper, in order to provide a comparative study, we consider spectral features and dispersion characteristics of a Bragg reflection waveguide having either periodic or aperiodic configuration of layers in the cladding. For an aperiodic configuration we have a choice between three well known aperiodic chains produced through substitution rules of Fibonacci [22], Thue–Morse [23], and Kolakoski [24] sequences.

2. Theoretical description

We consider a Bragg reflection waveguide (Fig. 1a) that is made of a low-index core layer (in particular, an air gap) sandwiched between two identical either periodic or aperiodic one-dimensional Bragg mirrors formed by stacking together layers of two different sorts Ψ and Υ, which have thicknesses d_Ψ, d_Υ and refractive indices n_Ψ and n_Υ, respectively. The numbers of constitutive layers of each sort are defined as N_Ψ and N_Υ. The structure inhomogeneity (i.e. the variation of the refractive index) extends along the z-axis, and in this direction the system is finite, i.e. we suppose that mirrors on either side of the core layer consist of a finite number N of the constitutive layers. In other two directions x and y the structure is invariant and infinite. In such a geometry the axis of symmetry of the structure under study corresponds to the middle of the core layer which is at the line $z=0$, where the core layer has thickness $2d_g$ and refractive index n_g.

Therefore, we study a Bragg reflection waveguide having a core layer with thickness $2d_g = \lambda_{qw}/2n_g$, where $\lambda_{qw} = 1$ μm. As constituents for the cladding composition we utilize a combination of layers made of GaAs and oxidized AlAs, whose refractive indices at the given wavelength λ_{qw} are $n_\Psi = 3.50$ and $n_\Upsilon = 1.56$, respectively. The thicknesses d_Ψ and d_Υ are chosen to be 74.5 nm for GaAs layers and 208.2 nm for AlAs-oxide layers in order to provide the operation bandwidth to be within the first telecommunication window.

As an aperiodic configuration three alternative designs of the waveguide's mirrors are investigated. Thus, a comparative study between the waveguides with the multilayered cladding altered according to the substitutional rules of Fibonacci [22], Thue–Morse [23], and Kolakoski [24] sequences is provided (see, Appendix A).

In the chosen structure configuration, each guided mode of TE polarization $\{E_x, H_y, H_z\}$ or TM polarization $\{H_x, E_y, E_z\}$ propagates along the y-axis with its own propagation constant β. As the mirrors on each side of the waveguide core layer are the same (i.e. the Bragg reflection waveguide is symmetrical about the z-axis, $n(-z) = n(z)$, as it is depicted in Fig. 1b–e), the equations for waves travelling back and forth inside the channel regardless of the type of polarization can be joined on the boundaries $z = d_g$ and $z = -d_g$ into the next system

$$\begin{cases} a_0 \exp(-ik_{zg}d_g) = Rb_0 \exp(ik_{zg}d_g), \\ b_0 \exp(-ik_{zg}d_g) = Ra_0 \exp(ik_{zg}d_g), \end{cases} \tag{1}$$

from which the relation between amplitudes can be found

$$b_0 = a_0 R \exp(2ik_{zg}d_g). \tag{2}$$

Here $k_{zg} = k_0(n_g^2 - n_{eff}^2)^{1/2}$ is the transverse wavenumber in the core, $n_{eff} = \beta/k_0$ is introduced as an effective refractive index for each particular guided mode, $k_0 = \omega/c$ is the free space wavenumber, and R is the complex reflection coefficient of the Bragg mirror which is depended on the wave polarization. The reflection coefficient R can be derived engaging the transfer matrix formalism [18–20] (see, Appendix B).

Eliminating amplitudes a_0 and b_0 from system (1), the dispersion equation for the guided modes of the Bragg reflection waveguide is obtained as

$$1 - R^2 \exp\left[4ik_0 d_g \sqrt{n_g^2 - n_{eff}^2}\right] = 0. \tag{3}$$

This equation is further solved numerically to find out a function of the propagation constant β versus frequency ω. The resulting propagation constant β is sought in the field of complex numbers due to the existence of intrinsic losses in the waveguide constitutive materials and energy leakage through the outermost layers because the number of layers N in the Bragg mirrors is a finite quantity.

The proper selection of the constitutive materials suggests the preference of substances with low internal losses. According to [25] the imaginary parts of the dielectric constants of the chosen GaAs and oxidized AlAs are negligibly small within the wavelength region of interest. Therefore, the main source of losses in the Bragg reflection waveguides under consideration is the energy leakage through their finite cladding. These losses can be estimated via the expression [5]:

$$\text{Loss [dB/cm]} = \frac{-\lambda \ln|R|}{40 n_g d_g^2 \sqrt{1 - (\lambda/4n_g d_g)^2}}. \tag{4}$$

From our estimation for the lowest modes presented in Fig. 2 it follows that the level of losses decreases exponentially with N (see, also discussions on this matter in [5,26]), and leakage of the TM mode is much greater than that of the TE mode. The leakage is also greater for the waveguides with an aperiodic arrangement of the cladding compared with the periodic system. Thus, the criterion of smallness of the imaginary part of β when classifying the waveguide modes can be satisfied by setting the number N to an

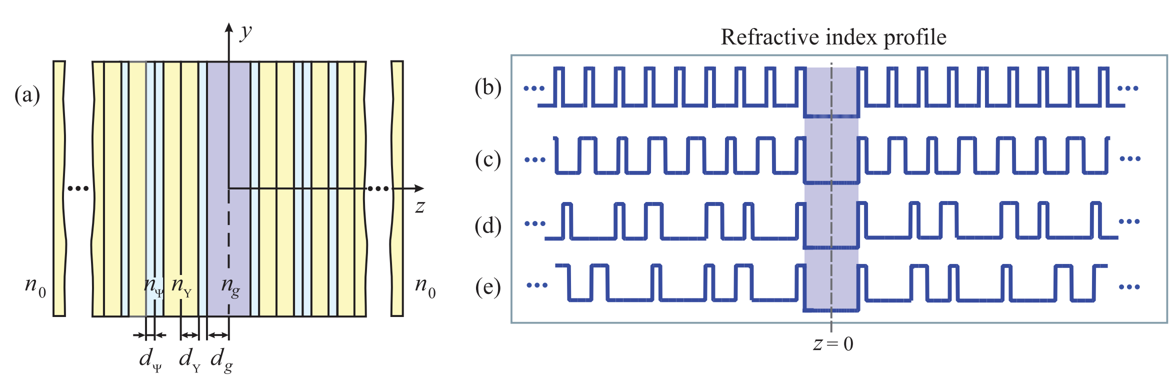

Fig. 1. (a) The schematic of a symmetrical Bragg reflection waveguide that consists of a core layer sandwiched between two aperiodic mirrors. Index profiles of the waveguide's cladding where layers are arranged according to the generation rules of (b) periodic, (c) Fibonacci, (d) Thue–Morse, and (e) Kolakoski sequences.