Quantum Electronics

FIBER AND INTEGRATED OPTICS

Bandgap modes in a coupled waveguide array

Quantum Electronics **39** (8) 770 – 773 (2009)

PACS numbers: 42.82.Ds; 42.82.Et
DOI: 10.1070/QE2009v039n08ABEH014006

Bandgap modes in a coupled waveguide array

B.A. Usievich, J.Kh. Nurligareev, V.V. Svetikov, V.A. Sychugov

***Abstract*. This work examines a waveguide array that consists of ten Nb_2O_5/SiO_2 double layers and supports a 0.63-μm surface wave. The deposition of a Nb_2O_5 capping layer on top of the waveguide array enables a marked increase in the wave field intensity on its surface. The efficiency of surface-wave excitation in the Kretschmann configuration can be optimised by adjusting the number of double layers. We analyse the behaviour of the Bragg mode in relation to the thickness of the layer exposed to air and the transition of this mode from the second allowed band to the first through the bandgap of the system. In addition, the conventional leaky mode converts to a surface mode and then to a guided mode.**

Keywords: *surface waves, periodic waveguide array, propagation constant.*

1. Introduction

Finite arrays of coupled waveguides are at present widely used in a variety of applications. Periodic waveguide arrays can be thought of as one-dimensional (1D) photonic crystals [1, 2]. In particular, such systems have allowed bands, where mode propagation is possible, and bandgaps, in which there are no mode propagation constants. This strict separation is valid only for an infinite waveguide array. In a finite system, the separation of the bands is disturbed, and its bandgap may contain leaky modes and even guided modes. The former modes may have a maximum in their field distribution near the boundary of the system and a field envelope that falls off exponentially with depth. Such modes are usually referred to as surface modes (surface waves) and can be used in sensing applications with Kretschmann excitation [3].

Consider in detail a waveguide array on a glass substrate with a refractive index $n_s = 1.52$. The array is composed of ten Nb_2O_5/SiO_2 double layers of thicknesses $h_{Nb_2O_5} =$ 110 nm and $h_{SiO_2} = 180$ nm, with refractive indices $n_{Nb_2O_5} = 2.27$, $n_{SiO_2} = 1.48$. According to our calculations, this system supports a 0.63-μm surface mode at its interface with air, with an effective refractive index $n^* = 1.159$. This value lies within the bandgap of the system, located between 1.13735 and 1.77325. The TE surface mode can be excited in the waveguide array using a He – Ne laser ($\lambda = 0.63$ μm), by launching the laser beam through the substrate, as was demonstrated in experiment [2].

When surface waves are used in sensing devices, a number of problems arise which we seek to resolve in what follows. These are the optimisation of surface-wave excitation, maximisation of the field at the interface where the wave localises and identification of the mechanism underlying the generation of surface waves at the waveguide – air interface. In addressing the last issue, we will use the concept of Bragg modes [4]. Bragg modes are modes N and $N+1$ (N is the number of waveguides in the system) whose effective refractive index in a symmetric waveguide array considered earlier lies in allowed bands near the bandgap. We call them Bragg modes because they are excited through the end face of the waveguide array at the Bragg angle.

2. Interfacial field

Since the system under consideration, composed of ten Nb_2O_5/SiO_2 double layers, has been shown to support a surface mode, we begin with the second problem. The field in a surface wave at an interface can be increased by depositing a thin (no thicker than 50 nm) Nb_2O_5 capping layer on top of the ten double layers. In evaluating surface-wave parameters, we rely on the results of an earlier study [5], which described an approach to calculating the spectrum and radiative loss of leaky modes in multilayer optical waveguides. The approach is based on two ideas: the use of the exact finite difference method (EFDM) instead of the commonly employed transfer matrix method (TMM) and a new, approximate procedure for calculating the attenuation coefficient of leaky modes, which asymptotically approaches the exact one as the attenuation decreases. This procedure for calculating leaky modes can be successfully applied because a surface mode in a coupled waveguide array is a leaky mode [6].

The calculational approach proposed in [5] is illustrated in Fig. 1 by the dependence of the attenuation coefficient of a leaky wave, α, on the effective refractive index of the mode, n^*, for a waveguide array consisting of ten Nb_2O_5/SiO_2 double layers plus one Nb_2O_5 layer of thickness $h = 0$, 10, 20, 30 and 40 nm. The minima in the curves are due to the leaky modes of the system. Each curve, corresponding to its own thickness h, has three dips, each

B.A. Usievich, J.Kh. Nurligareev, V.V. Svetikov, V.A. Sychugov
A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: borisu@kapella.gpi.ru

Received 14 November 2008; revision received 5 March 2009
Kvantovaya Elektronika **39** (8) 770 – 773 (2009)
Translated by O.M. Tsarev

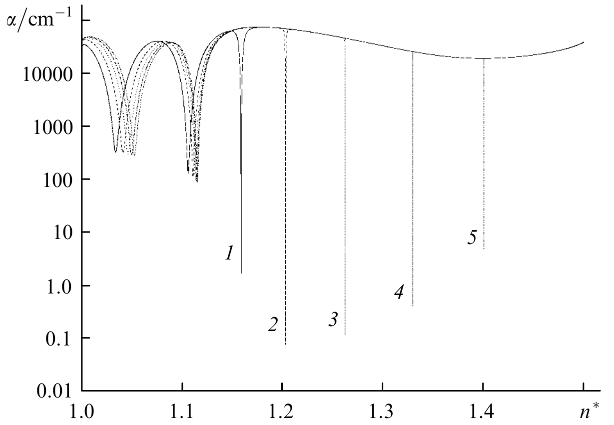

Figure 1. Optical loss coefficient as a function of the effective refractive index of modes, n^*, for a Nb_2O_5/SiO_2 waveguide array capped with a Nb_2O_5 layer of thickness $h = 0$ (*1*), 10 (*2*), 20 (*3*), 30 (*4*) and 40 nm (*5*).

corresponding to a leaky mode, only one of which is a surface mode. The dips in $\alpha(n^*)$ for the surface mode are substantially narrower than those for the conventional leaky modes. Increasing the thickness of the cap layer, h, produces only slight changes in the parameters of the conventional leaky modes, whereas the effective refractive index of the surface mode rises considerably, and the width of the resonance and, hence, the associated radiative loss drop markedly.

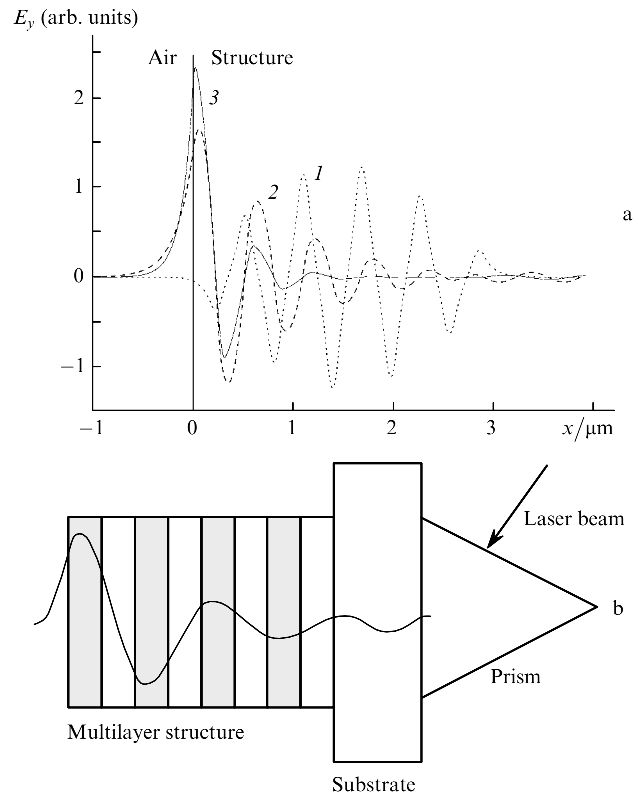

Figure 2. (a) Mode field distributions in (*1, 2*) the uncapped waveguide array and (*3*) the same waveguide array capped with a 30-nm Nb_2O_5 layer. (b) Schematic of surface-wave excitation in the Kretschmann configuration.

Figure 2 shows the field distributions of two Bragg modes, one of which is a surface mode, in the uncapped waveguide array (ten Nb_2O_5/SiO_2 double layers) and that of a surface wave in the same waveguide array capped with a 30-nm-thick Nb_2O_5 layer. As seen, the Nb_2O_5 capping layer increases the surface-wave amplitude by 50 %.

3. Optimal surface-wave excitation conditions in a waveguide array

Further optimisation of the Nb_2O_5 film thickness depends to a significant degree on dissipative losses and the radiative loss of surface waves in the waveguide array. The relationship between these losses determines the optimal surface-wave excitation conditions in the Kretschmann configuration. In this configuration, a surface wave is excited by a beam coupled by a high-index prism into the waveguide array through a glass substrate coated with dielectric layers. Because the surface wave is a leaky mode, its propagation across the waveguide array is accompanied by light leakage to the substrate. Since this effect is reversible, the surface wave may also be excited by a 3D wave incident from the substrate at an appropriate angle. The leakage rate and excitation efficiency are determined by the radiative loss coefficient of the mode, which depends on the number of double layers, N, and the position of the effective refractive index in the bandgap of the multilayer structure.

The minimum penetration depth of a field in a periodic waveguide structure is known to correspond to its midgap. For this reason, as n^*_{sur} approaches the bandgap edge, the surface-wave leakage to the substrate increases, as does the coupling between the incident and surface waves. It is also known that, varying the number of double layers in a waveguide array, one can achieve efficient Kretschmann excitation [7]. Ramirez-Duverger et al. [7], however, do not explain why the number of double layers used in their work is optimal for excitation. According to our estimates, excitation is optimal when (like in the case of polaritons [8]) the substrate leakage loss of the mode being excited is roughly equal to its absorption and scattering losses.

The surface-mode excitation efficiency in a waveguide array can be estimated from the reflectance R of the coupling prism base as a function of the number of double layers, N. Under optimal excitation conditions, $R(N)$ has the largest dip. Figure 3 shows the $R(N)$ curve of a

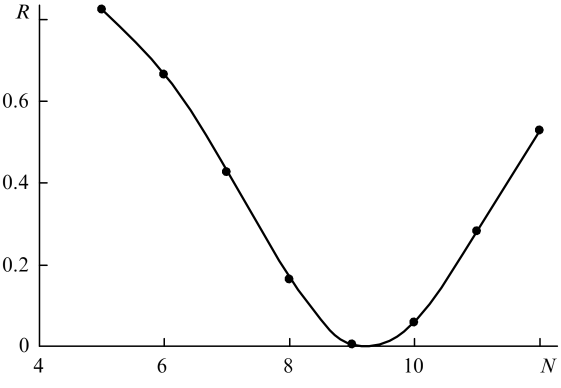

Figure 3. Reflectance in the Kretschmann configuration as a function of the number of Nb_2O_5/SiO_2 double layers in the system.

Nb_2O_5/SiO_2 structure at imaginary parts of permittivity of the Nb_2O_5 and SiO_2 films of 7×10^{-4} and 10^{-4}, respectively. Note that these ε'' values may appear too high, but losses in thin films may considerably exceed those in bulk materials, in particular because of the scattering loss. As seen in Fig. 3, the structure composed of ten double layers is nonoptimal for the given loss level, and the number of Nb_2O_5/SiO_2 double layers must be reduced to nine in order to maximise the surface-wave excitation efficiency at the interface with air.

At the above ε'' values of the films, the deposition of a 30-nm Nb_2O_5 capping layer on top of nine double layers does not ensure the optimal surface-mode excitation conditions in the system because of the changes in the radiative loss of surface waves, and the number of double layers must be reoptimised. Our calculations indicate that the optimal number of double layers is then $N = 4$, with $n^*_{\text{sur}} = 1.33$. When the number of double layers is varied, the field amplitude at the waveguide–air interface remains increased because it is influenced only by the near-surface layers.

4. Bragg modes in a waveguide array with a surface wave at its interface with air

As pointed out earlier [4], the mode spectrum of a finite waveguide array has two Bragg modes. The field distributions of the Bragg modes in the uncapped structure are shown in Fig. 2. One of these modes is guided, and the other, with a low effective refractive index, is leaky. The latter has a higher field amplitude at the interface with air and is thus referred to as a surface mode of the waveguide array. The Bragg mode distribution presented in Fig. 2 stems from the fact that the uncapped waveguide array (ten double layers) is composed of single-mode waveguides, and the number of guided modes in the system coincides with the number of waveguides, N. Therefore, the order of the first Bragg mode is N, and it is the last mode in the first allowed band. The order of the second Bragg mode is $N + 1$, and it is the first mode in the second allowed band. It follows from Fig. 3 that a surface mode may exist at any number of double layers in the array, but the Kretschmann excitation efficiency depends on N. To gain insight into the generation of a surface mode, consider how its effective refractive index and field distribution depend on the thicknesses of the layers that form the surface cell of the system, in which, as we already know, the surface wave propagates.

The thickness of the last SiO_2 layer has a significant effect on the field distribution of this Bragg mode: with decreasing h_{SiO_2}, the surface mode converts to a conventional leaky mode (the prominent field maximum at the interface disappears), and its effective refractive index decreases (Fig. 4). At $h_{SiO_2} = 0$, we obtain a waveguide array composed of nine double layers and a 110-nm Nb_2O_5 layer, with no surface wave.

Also shown in Fig. 4 is the $n^*(h_{Nb_2O_5})$ curve for the 11th mode of a system consisting of ten Nb_2O_5/SiO_2 double layers and a Nb_2O_5 layer of varied thickness. As pointed out above, the deposition of a 30-nm Nb_2O_5 capping layer markedly increases the surface-wave field at the waveguide-air interface. At larger Nb_2O_5 layer thicknesses, the leakage decreases further, and at $h_{Nb_2O_5} = 110$ nm the mode becomes guided, with $n^* = 1.7723$, which is near the upper bandgap edge (1.7735). Thus, with increasing the capping

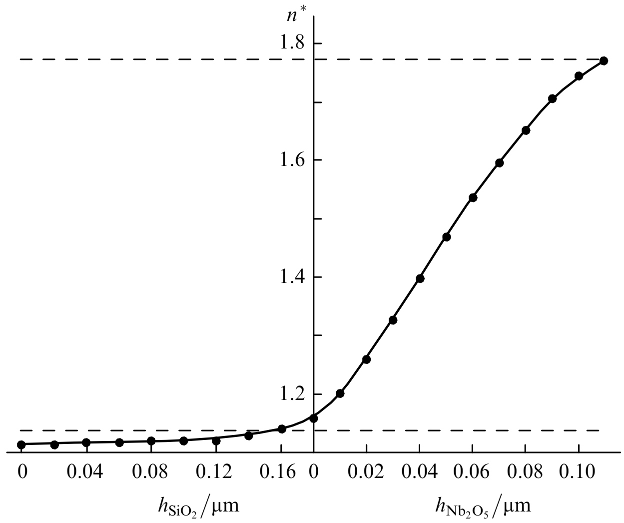

Figure 4. Effective refractive index n^* of the $m = 11$ mode as a function of the thicknesses of the last double layer. The dashed lines indicate the bandgap edges.

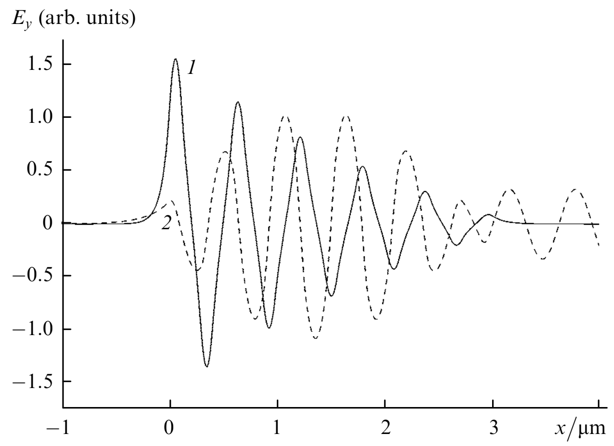

Figure 5. Field distributions of the (*1*) $m = 11$ and (*2*) $m = 12$ Bragg modes in a waveguide array composed of ten Nb_2O_5/SiO_2 double layers 110/180 nm in thickness and a 110-nm Nb_2O_5 capping layer.

layer thickness this mode becomes the first Bragg mode of the system. The $m = 12$ mode, with an effective refractive index $n^*_{12} = 1.119$ (falling in the second allowed band of the waveguide array), is then the second Bragg mode (Fig. 5).

Thus, increasing the total thickness of the structure by raising the number of SiO_2 and Nb_2O_5 layers increases the effective refractive index of the Bragg mode in the second allowed band, bringing this mode to the bandgap and making it a surface mode. Further increasing the thickness of the structure makes this mode guided. Unusually enough, the guided mode also has a prominent field maximum at the boundary of the structure, i.e., it is in effect a surface mode, even though it cannot be excited in the Kretschmann configuration.

5. Conclusions

Analysis of a coupled waveguide array indicates that, for the array to support a surface mode, it is necessary to properly select the combination of dielectric layers (with a large refractive-index difference) and to determine the guiding layer thicknesses corresponding to single-mode waveguiding and the gap thickness at which the number of guided modes is equal to the number of waveguides in the system. The interfacial wave field can be enhanced by depositing a high-index capping layer on the waveguide array. The number of double layers should then be optimised for specific loss values of the constituent layers. The surface wave thus realised on a 1D photonic crystal will be a quite effective tool for probing unknown layers, including biolayers, deposited on the waveguide system.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 02-07-00064).

References

1. Robertson W.M., May M.S. *Appl. Phys. Lett.*, **74**, 1800 (1999).
2. Usievich B.A., Nurligareev J.Kh., Svetikov V.V., Sychugov V.A. *Opt. Spektrosk.*, **106**, 641 (2008).
3. Kretschmann E. *Z. Phys.*, **241**, 313 (1971).
4. Usievich B.A., Nurligareev J.Kh., Sychugov V.A., Golant K.M. *Kvantovaya Elektron.*, **35**, 554 (2005) [*Quantum Electron.*, **35**, 554 (2005)].
5. Golant E.I., Golant K.M. *Zh. Tekh. Fiz.*, **76**, 99 (2006).
6. Usievich B.A., Svetikov V.V., Nurligareev J.Kh., Sychugov V.A. *Kvantovaya Elektron.*, **37**, 981 (2007) [*Quantum Electron.*, **37**, 981 (2007)].
7. Ramirez-Duverger A.S., Gaspar-Armenta J., Garcia-Llamas R. *Opt. Commun*, **227**, 302 (2007).
8. Chen W.P., Chen J.M. *J. Opt. Soc. Am. B*, **71**, 189 (1981).