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Waveguiding through a two-dimensional metallic photonic crystal

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Summary

We present a two-dimensional (2D) finite-difference time domain simulation of the propagation of light through linear and bent channels in metallic photonic crystals. We took as a starting point the Bozhevolnyi experiment, consisting of the scattering of surface plasmons by a 2D structure of finitely sized periodic gold dots arranged in a triangular lattice of 400-nm period. We model injection and propagation of light through linear channels of different widths. We also study the behaviour of light in the presence of a 90° bent line defect made in the structure. We show that the confinement depends on the orientation of the input and output line defects. The two cases of ΓM and ΓK orientations are considered and a spectral study for five different wavelengths is carried out.

Introduction

Many experimental and theoretical studies have been devoted to photonic crystals because they have many potential technological applications: filters, lossless mirrors, substrates for microwave antennas, efficient light emitters, etc. Among these applications, planar photonic crystals could provide a solution to enhancing the integration of optical components to a scale comparable with light wavelengths. Most of the studies of planar photonic crystals have been performed with dielectric structures. Peeters *et al.* (2000) used a focused ion beam (FIB) to produce a photonic structure into ridge waveguides in Si_3N_4 . Quidant *et al.* (2002) constructed heterowire structures by electron beam lithography and reactive ion etching on a TiO_2 film. These previous structures are rather one-dimensional (1D) photonic crystals. Two-dimensional (2D) photonic structures have also been fabricated and studied (Loncar *et al.*, 2000; Mulin *et al.*, 2001; Gérard *et al.*, 2002; Talneau *et al.*, 2002).

A scanning near-field optical microscope is often used to observe light propagation and diffraction in such structures (Peeters *et al.*, 2000; Mulin *et al.*, 2001; Gérard *et al.*, 2002; Quidant *et al.*, 2002). A group from the University of Exeter, U.K. has published a series of papers on the photonic band structure of textured metallic surfaces. They compared far-field experiments on surface plasmon dispersion with calculations obtained by a conical version of the differential formalism of Chandezon *et al.* (Barnes *et al.*, 1996; Salt & Barnes, 2000, and references therein).

Recently, Bozhevolnyi *et al.* have published interesting papers demonstrating surface plasmon photonic band gap effects on planar 2D metallic structures (Bozhevolnyi & Volkov, 2001a,b; Bozhevolnyi *et al.*, 2001a,c). The surface plasmon is produced by attenuated total reflection in the Kretschmann configuration on a glass–gold–air structure. The metallic layer has a thickness of 45 nm. On the metal–air interface, a 2D planar crystal is created with gold dots (200 nm in diameter, 45 nm in height) arranged in a triangular lattice of 400-nm period. Surface plasmon propagation and diffraction are studied by use of a scanning near-field optical microscope in the collection mode. The experiments clearly show band gap effects in waveguides made by line defects in the photonic structure (Bozhevolnyi & Volkov, 2001a; Bozhevolnyi *et al.*, 2001a,b).

The purpose of this paper is to present preliminarily results from experiments in which the Bozhevolnyi set-up is modelled by using a 2D-FDTD method (Taflove, 1998; Taflove & Hagness, 2000).

Principle of the calculations

The rigorous theoretical description of the Bozhevolnyi experiments is a highly complex task, because it is a true 3D diffraction problem with many nanometric scatterers (dots) made from a pure metal.

However, as a first attempt, a 2D model could lead to significant results. This assumption is often used in theoretical studies of

planar photonic crystals (e.g. Bozhevolnyi *et al.*, 2001a; Talneau *et al.*, 2002). In the case of surface plasmons (SP), the evanescent character of the illumination where the amplitude of the SP decays exponentially into vacuum can justify this approach: in this paper the structure is then considered to comprise infinite rods of pure metal arranged into a triangular grating of 400-nm period. The diameter of a single rod is equal to 200 nm. This 2D approach was previously used by Bozhevolnyi & Volkov (2001b).

In this paper, the incident field is a 2D Gaussian beam or a plane wave. Because in the experiments the SP excitation was the result of an electric field component parallel to the rod axis, we choose this configuration in our model. A 'home-made'

FDTD code has been developed including the perfectly matched layer (PML) technique (Berenger, 1994) to solve the parasitical reflections at the edges of the grid. Moreover, we have taken into account the dispersion properties of the metal, which are described by a Drude model.

Results

Waveguiding in linear channels

We first present results of FDTD calculations showing the propagation along line defects of various widths. The modelled structure is shown in Fig. 1(a,d), in which the size of the

Fig. 1. Propagation through linear channels made in a triangular grating of gold rods, along the ΓM direction (a–c) and the ΓK direction (d–f). The wavelength of the incident plane wave is set to 750 nm (b,e) and 1550 nm (c,f).

computing window is $21\text{ }\mu\text{m} \times 21\text{ }\mu\text{m}$. By deleting lines of rods parallel to ΓM or ΓK , waveguides of different widths are created (see Fig. 1a,d for the widths). The length of each channel is $16\text{ }\mu\text{m}$.

This width is a ‘mean’ value for guides along the ΓK direction because their cross-section is irregular. The incident beam is a plane wave, and the direction of incidence is normal to the structure and orientated parallel to the waveguide direction, i.e. along ΓM (Fig. 1a–c) or ΓK (Fig. 1d–f). In all the calculations, the electric field is parallel to the axis of the rods. We have performed the calculations for two wavelengths: one in the red region of the spectrum ($\lambda = 750\text{ nm}$, Fig. 1b,e) and the other in the telecom infrared band ($\lambda = 1550\text{ nm}$, Fig. 1c,f). In all the figures, we have plotted the modulus of the electric field.

On the right-hand side of the images in Fig. 1, we can see patterns created by interference between the incident field and the diffracted fields on the apertures of the waveguides. The diffracted field emitted at the end of the waveguides is also visible on the left-hand side of the images. When light injection in a guide is efficient, a standing wave pattern can be observed in the channels. There is no significant coupling between the parallel waveguides.

Interesting effects are obtained for the narrowest waveguide. For $\lambda = 750\text{ nm}$, light is guided in this channel along the ΓM direction but not along ΓK and there is no injection for $\lambda = 1550\text{ nm}$, either for the ΓM direction or for the ΓK direction.

It is also important to note that, outside the channels, the penetration depths in the crystal structure are very different for the two directions of injection and for the two wavelengths: the smallest decay length is obtained for injection along ΓK and for $\lambda = 1550\text{ nm}$ where incident light is stopped just in front of the first row of rods (see left edge of Fig. 1c,f).

Propagation along a 90° bent line

Figure 2 shows a top view of the structure. The 90° bent line defect is made in the triangular grating by removing two perpendicular lines of rods. In order to connect these two channels, another small line is removed. Thus, the two principal lines are necessarily in the directions ΓK or ΓM . The length of the ΓK -orientated line is equal to $5.1\text{ }\mu\text{m}$, whereas the line directed along ΓM is $7.6\text{ }\mu\text{m}$ in length. The connecting line is in the ΓM direction and has a length of $3.2\text{ }\mu\text{m}$. The total length of removed rods corresponds to a $15.9\text{-}\mu\text{m}$ -long line.

In this section, in order to model injection of light, the illumination is provided by a Gaussian polarized beam with a beam-waist of $4\text{ }\mu\text{m}$ and centred on the entrance of the line defect. Such a beam is a 2D version of the incident light created by a monomode optical fibre. We chose to study the spectral response for five different wavelengths (727, 750, 785, 815 and 850 nm), which are the experimental wavelengths used in Bozhevolnyi *et al.* (2001c).

Fig. 2. Schematic diagram of the structure of the 90° bent line. Note that only one row of rods is removed in order to generate the channel.

Figure 3 show the amplitude distributions of light, for the five different wavelengths and for two directions of injection: injection along ΓM and exit along ΓK (Fig. 3a–e) and injection along ΓK and exit along ΓM (Fig. 3a’–e’).

The transmission along the 90° bent line is very sensitive to the wavelength. For $\lambda = 727\text{ nm}$ (Fig. 3a), the light is guided into the ΓM input line but does not bypass the first corner.

For $\lambda = 750\text{ nm}$, the light remains confined towards the small connecting line (see Fig. 3b). The light seems to have stopped at the second corner. No light can be found at the end of the structure.

When the wavelength is 785 nm , confinement is localized at both the two corners but the field amplitude is larger at the second corner. A small proportion of the light seems to reach the exit. This enhancement of the transmission is increased for $\lambda = 815\text{ nm}$. In Fig. 3(d) light is guided through all the line defects both in the ΓK and the ΓM directions. The losses at the two corners are very weak. At 850 nm (Fig. 3e) the line defect acts as a waveguide and most of the injected light is transmitted and diffracted at the output.

Similar results are obtained when light is injected along the ΓK direction: the transmission efficiency increases with wavelength. Note also in this case that the injection seems more difficult: compare the intensity distribution of Fig. 3(a,a’) with Fig. 3(b,b’).

In order to compare the transmission efficiency of the channels for different wavelengths, we have plotted in Fig. 4 a cross-section of the square modulus of the electric field along a line located just at the exit of the 90° bent line.

For injection along ΓM , if the incident intensity is normalized to 1, the maxima of the five curves are 0.004, 0.005,

Fig. 3. Field pattern (in greyscale) when an incident Gaussian beam is injected along the ΓM line defect (a–e) and along the ΓK line defect (a'–e'). $\lambda = 727$ nm (a,a'), $\lambda = 750$ nm (b,b'), $\lambda = 785$ nm (c,c'), $\lambda = 815$ nm (d,d') and $\lambda = 850$ nm (e,e').

Fig. 4. Cross-sections of the square modulus of the electric field at the exit of the bent line, for the five wavelengths used (a–e are as in Fig. 3).

0.03, 0.47 and 1.4 for $\lambda = 727, 750, 785, 815$ and 850 nm, respectively. The scale of the y -axis in Fig. 4 has been truncated in order to visualize the smallest curves (a and b).

Conclusion

We have presented a 2D FDTD study of injection, propagation and transmission along linear and 90° bent line created in a 2D metallic crystal. We have studied two directions of injection of light and shown the influence of the guide width and of the wavelength. The results are our first attempt to describe the optical properties of metallic planar photonic crystals.

The dispersion properties of the metal are appropriately taken into account in our calculations. We have succeeded in reproducing qualitatively the experimental results (light guiding and confinement in linear and bent channels). The results shown here suggest that narrow guides can be adapted for useful applications: they are monomode and more selective in wavelength. Their technological realization is possible using a FIB.

A precise quantitative comparison between theory and experiments requires further knowledge of the experimental parameters (exact shape of the dots, of the channels and exact values of the permittivity of the pure metal) and the use of a 3D model and 3D computing code.

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References

- Barnes, W.L., Preist, T.W., Kitson, S.C. & Sambles, J.R. (1996) Physical origin of photonic energy gaps in the propagation of surface plasmons on gratings. *Phys. Rev. B*, **54**, 6227–6244.

- Berenger, J.-P. (1994) A perfectly matched layer for the absorption of electromagnetic waves. *J. Comput. Phys.* **114**, 185–200.
- Bozhevolnyi, S.I., Erland, J., Kristjan, L., Skovogaard, P.M.W. & Hvam, J.M. (2001a) Waveguiding in surface plasmon polariton band gap structures. *Phys. Rev. Lett.* **86**, 3008–3011.
- Bozhevolnyi, S.I. & Volkov, V.S. (2001a) Bend loss in surface plasmon polariton band-gap structures. *Appl. Phys. Lett.* **79**, 1076–1078.
- Bozhevolnyi, S.I. & Volkov, V.S. (2001b) Multiple-scattering dipole approach to modeling of surface plasmon polariton band gap structures. *Opt. Commun.* **198**, 241–245.
- Bozhevolnyi, S.I., Volkov, V.S., Kristjan, L. & Erland, J. (2001b) Observation of propagation of surface plasmon polaritons along line defect in a periodically corrugated metal surface. *Opt. Lett.* **26**, 734–736.
- Bozhevolnyi, S.I., Volkov, V.S. & Loesson, K. (2001c) Surface plasmon polariton propagation along a 90° bent line defect in a periodically corrugated metal surface. *Opt. Commun.* **196**, 41–45.
- Gérard, D., Berguiba, L., de Fornel, F., Salomon, L., Seassal, C., Letartre, X., Rojo-Romeo, P. & Viktorovitch, P. (2002) Near-field probing of active photonic-crystal structures. *Opt. Lett.* **27**, 173–175.
- Loncar, M., Nedeljkovic, D., Doll, T., Vuckovic, J., Scherer, A. & Pearsall, T.P. (2000) Waveguiding in planar photonic crystals. *Appl. Phys. Lett.* **77**, 1937–1939.
- Mulin, D., Girard, Ch., Colas-Des Francs, G., Spajer, M. & Courjon, D. (2001) Near-field optical probing of two-dimensional photonic crystals: theory and experiment. *J. Microsc.* **202**, 110–116.
- Peeters, C., Flück, E., Otter, A.M., Balistreri, M.L.M., Korterik, J.P., Kuipers, L. & van Hulst, N.F. (2000) Photon scanning tunneling microscopy of tailor-made photonic structures. *Appl. Phys. Lett.* **77**, 142–144.
- Quidant, R., Weeber, J.-C., Dereux, A., Peyrade, D., Girard, Ch. & Chen, Y. (2002) Spatially resolved photonic transfer through mesoscopic heterowires. *Phys. Rev. E*, **65**, 036616.
- Salt, M.G. & Barnes, W.L. (2000) Flat photonic bands in guided modes of textured metallic microcavities. *Phys. Rev. B*, **61**, 11125–11135.
- Taflove, A. (1998) *Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Artech House, Norwood, MA, U.S.A.
- Taflove, A. & Hagness, S.C. (2000) *Computational Electrodynamics, the Finite-Difference Time-Domain Method*. Artech House, Norwood, MA, U.S.A.
- Talneau, A., Le Gouezigou, L., Bouadma, N., Kafesaki, M., Soukoulis, C.M. & Agio, M. (2002) Photonic-crystal ultrashort bends with improved transmission and low reflection at $1.55\ \mu\text{m}$. *Appl. Phys. Lett.* **80**, 547–549.