Double Negative Metamaterial Inclusions in Photonic Crystal Based Resonant Cavities

R. Letizia and D. Pinto

Engineering Department
Lancaster University
Bailrigg
Lancaster
United Kingdom
LA1 4YW
Tel: +44 (0)1524 592763; email: r.letizia@lancaster.ac.uk

Abstract

In this paper the inclusion of double negative metamaterial (MTM) layers to form the defect region of a hexagonal photonic crystal cavity is investigated. Numerical results show that the MTM inclusion gives rise to a single monopole resonant mode for TM field with enhanced localization effect of the defect state and increased quality factor. This property may result in the design of improved PhC cavities for sensing applications.

1. Introduction

In 90's the pioneering work by John Pendry *et al.* [1] introduced the research community to the physical realisation of artificial materials with unusual characteristics, and the earlier Veselago's vision of having a material with both negative permittivity and permeability [2] could materialise in the active research field of Metamaterials (MTMs). Since then, MTM designs, based on arrays of discrete cells with geometrical features that are significantly smaller than the wavelength of the applied radiation, have increased in complexity and sophistication, to the point that precisely controlled gradients in both effective permittivity and permeability can be introduced to form advanced lenses and optics [3], or even invisibility cloaks [4]. On the other hand, Photonic bandgap (PBG) materials, also known as Photonic Crystals (PhCs), have been established in the research environment because of their unique capability to control the propagation of the light. The main feature in PhCs is the existence of one or more bands of optical frequencies in which no electromagnetic wave is allowed to propagate [5]. This property arises from the presence of a periodic pattern of the refractive index along one or more directions. Breaking the periodicity of a PhC permits the appearance of localised electromagnetic states inside the PhC at frequencies that otherwise are not allowed. Using this defect strategy, different devices have been realised such as filters [6], cavities [7], and many others.

In this work, a novel PhC microcavity sensor is presented. The structure is created by inserting a layer of double negative MTM in a hexagonal PhC cavity. The aim is to investigate the quality factor Q and sensitivity of the proposed sensor. The results show that the inclusion of MTM layer not only improves the cavity quality factor, but also increases the device sensitivity.

2. Numerical Method

The finite volume time-domain (FVTD) method has recently emerged as an efficient numerical tool for computational EM problems, combining the versatile meshing capabilities of finite elements

ISBN 978-952-67611-2-1

method in addition to being explicit as the popular finite difference time domain method [8]. Drude dispersion model is considered to simulate dielectric permittivity ε and magnetic permeability μ of the MTM inclusion in the operating frequency range, as follows

$$\varepsilon(\omega)=\varepsilon_0\left(1-\frac{\omega_{pe}^2}{\omega(\omega+i\Gamma_{pe})}\right);\mu(\omega)=\mu_0\left(1-\frac{\omega_{pm}^2}{\omega(\omega+i\Gamma_{pm})}\right) \tag{1}$$

where ε_0 and μ_0 are the dielectric permittivity and magnetic permeability of the free space, respectively, ω_p is the plasma frequency, and Γ_p is the damping coefficient. The material dispersions have been efficiently included in the FVTD by the use of Auxiliary Differential Equation (ADE) scheme.

3. Results

In this work a hexagonal PhC resonant cavity has been considered. The structure consists of a dielectric slab with refractive index n_1^2= 11.4 in which air holes (n_2 = 1.0) of radius r = 0.45 a have been drilled into a triangular pattern with lattice constant a = 0.650225μm, as shown in Fig. 1.

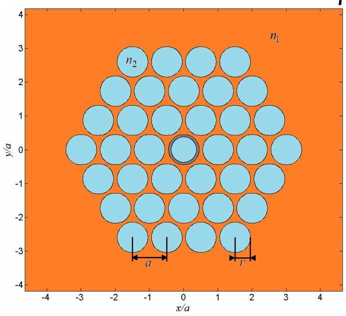
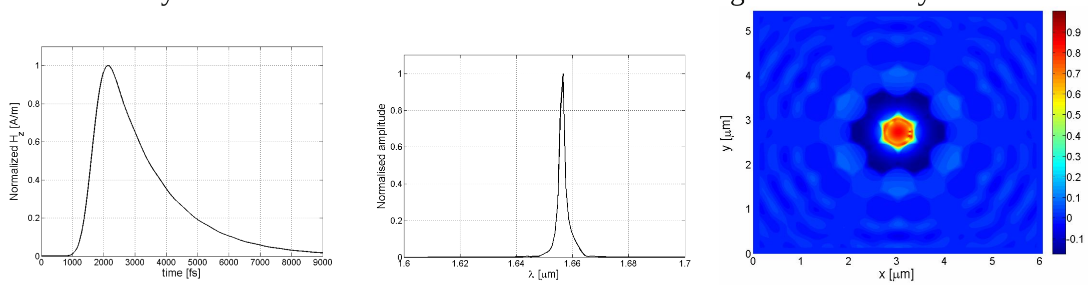


Fig. 1: Schematic diagram of the hexagonal PhC cavity with MTM inclusion in the central air hole

The cavity defect is formed by an inclusion of MTM layer surrounding the central air hole of the PhC. For all simulations, the Drude parameters Γ_{pe} and Γ_{pm} are set to zero while ω_{pe} and ω_{pm} are fixed to $2^{1/2}\omega$, so as to obtain ε_r=μ_r=-1. The same PhC hexagonal cavity with no MTM inclusion has been extensively studied in [9], where it has been shown that by removing the central air hole, the cavity behaves as a multimode resonant cavity for TM polarization field (magnetic field H perpendicular to the plane of periodicity of the PhC). However, it is worth mentioning that, in this work, the air hole is not removed and without the MTM inclusion the PhC hexagonal cavity does not present any resonant mode. In order to show that the MTM inclusion behaves like a defect for the PhC, a source consisting in a time domain pulse centered at λ_0=1.55 μm with a shape of a Gaussian bell positioned in the central air hole is used to excite the cavity. The envelope of the time domain evolution of the magnetic field H_z obtained from this simulation is shown in Fig. 2a. The exponential decay of the magnetic field H_z clearly indicates resonance in the cavity. By means of FFT of the time domain data, the wavelength of the resonant mode is calculated as shown in Fig. 2b. From this figure, it can be seen that the resonance is centered at λ = 1.657 μm and the quality factor Q of the cavity is found to be 970. In Fig. 2c, the electromagnetic field profile of the resonant mode is shown. This figure shows that the resonant mode is mainly localized inside the central air hole of the hexagonal PhC cavity.



a b c

Fig. 2: a) Envelope of the time domain evolution of the resonant mode; b) spectrum of the resonant mode; c) field profile of the resonant mode

This means that the electromagnetic field of the resonant mode can strongly interact with the substance which the central hole of the cavity is filled with. In order to show this property, different simulations have been run by varying the refractive index of the central hole of the PhC cavity from 1.0 to 1.3 with step 0.1. The resulting spectra and final results are shown in Fig. 3.

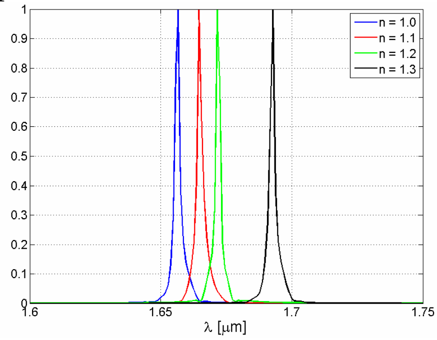


Fig. 3: Spectra of the resonant modes of the hexagonal PhC cavity for different values of the refractive indices of the central hole.

From this figure, it can be seen that for each case a shift in the resonant mode wavelength is obtained and for each case the resonant peaks can be clearly identified. The wavelength and the Q-factor of the resonant mode for each case simulated are calculated as follows: for the case of n=1.1, the resonant wavelength is at 1.665 μm and the Q-factor equals 700; for the case n=1.2, the resonant wavelength is at 1.672 μm and the Q-factor is 800; for the case n=1.3, the resonant wavelength is at 1.693 μm and the Q-factor is 870.

4. Conclusion

In this work, a FVTD method extended with the ADE technique has been used to investigate the effect of MTM inclusions in a PhC cavity. The field pattern distribution, the quality factor Q and resonant frequency spectrum of a hexagonal PhC cavity with a MTM inclusion have been accurately calculated. The MTM inclusion strongly confines the EM field of the resonant mode in the defect region, enhancing the field interaction with the substance which the central hole is filled with. This property can be used to design improved PhC cavities for sensing applications.

References

[1] J.B. Pendry, A.J. Holden, W.J. Stewart, and I. Youngs, Extremely Low Frequency Plasmons in Metallic Mesostructures, *Phys. Rev. Lett.*, vol. 76, no. 25, pp. 4773–4776, 1996.

[2] V.G. Veselago, The Electrodynamics of Substances with Simultaneously Negative values of e and m, *Sov. Phys. Usp*, vol. 10, no. 4, pp. 509-514, 1968.

[3] J. B. Pendry, Neagative Refraction Makes a Perfect Lens, *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966-3969, 2000.

[4] J. B. Pendry, D. Schurig, and D. R. Smith, Controlling Electromagnetic Fields, *Science*, vol. 312, no. 5781, pp. 1780-1782, 2006.

[5] J.D. Joannopoulos, R.D. Meade, and J.N. Winn, *Photonic Crystals: Molding the Flow of Light* NJ: Princeton Univ. Press, 1995.

[6] R. Costa, A. Melloni, and M. Martinelli, Bandpass Resonant Filters in Photonic-Crystal Waveguides, *IEEE Photon. Technol. Lett.*, vol. 15, pp. 401-403, 2003.

[7] A. Faraon, D. Englud, D. Bulla, B. Luther-Davies, B.J. Eggleton, N. Stoltz, P. Petroff, and J. Vučković, Local tuning of photonic crystal cavities using chalcogenide glasses, *Appl. Phys. Lett.*, vol. 92, pp. 043123-1 – 043123-3, 2008.

[8] D. Pinto, S.S.A. Obayya, Accurate perfectly matched layer finite-volume time-domain method for photonic bandgap devices, *IEEE Photon. Technol. Lett.*, vol. 20, pp. 339–34, 2008.

[9] D. Pinto, S.S.A. Obayya, 2D Analysis of multimode photonic crystal resonant cavities with the finite volume time domain method, *Opt. Quant. Electron.*, vol. 40, pp. 875-890, 2008.

ISBN 978-952-67611-2-1