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Ceramic electromagnetic bandgap structures for microwave and millimetre wave applications☆

Norbert Klein*, Michael Schuster, Daniel Parkot

Forschungszentrum Jülich GmbH, Institut für Schichten und Grenzflächen, D-52425 Jülich, Germany

Abstract

We have investigated defect resonances in two-dimensional electromagnetic bandgap structures made from sintered alumina ceramics. The particular emphasis of our studies was the analysis of quality factors of different types of defect resonances and the search for novel geometries aiming towards their controlled excitation. For the case of a two-dimensional hexagonal dielectric rod structure we have analysed the quality factors of resonant TM modes in an extended defect. We have identified modes with dielectric filling factor of less than thirty percent indicating the possibility of high Q values. In addition, we have demonstrated a defined excitation of such defect resonances by external waveguides. As a step toward a novel millimetre wave integrated circuit technology, we have demonstrated the defined excitation of 3D confined modes of a line defect in an air-suspended dielectric slab. Our results could pave the way to novel types of integrated millimetre circuits based either on LTCC or high temperature ceramics. Possible future applications are integrated low-phase noise oscillator circuits with potential use for optical communication networks, radar systems and point-to-multipoint communication links.

Keywords: Al_2O_3; Dielectric properties; Functional applications

1. Introduction

It is well known that in a spatially periodic arrangement of dielectric or metallic material the propagation of electromagnetic waves is forbidden for certain frequency bands.[1] Those frequency bands are called electromagnetic bandgaps, and the dielectric arrangement is called electromagnetic bandgap (EBG) structure or photonic crystal. When a point defect is introduced in the EBG lattice by local modification of the lattice parameters, localised modes with resonant frequencies may exist inside the bandgap.[2] Such a localised mode has a potential to be used as high Q resonator in various frequency ranges from the microwave range up to optical frequencies. A linearly extended defect can guide waves with high efficiency, thus allowing for the construction of beam splitters, sharp bend waveguides and coupling structures.[3–5]

Photonic crystals that are periodic in two dimensions only (2D photonic crystals) can provide a bandgap for every direction of propagation in the lattice plane of periodicity. It has been shown that in such a 2D type of photonic crystal the EBG behaviour is different for so-called TE and TM modes, which can be distinguished by having either their electric field (TM) or a magnetic field (TE) perpendicular to the 2D EBG lattice.[1,6] For TM waves the field confinement in the third dimension can be realised by arranging dielectric or metal rods of finite height (typically less than half the wavelength) between two parallel oriented metal plates. For TE modes the photonic crystal can be made by patterning a bulk dielectric material with periodic air holes. If a bulk dielectric material is used, it can be suspended in air in order to avoid the losses from the metal endplates. For appropriate dimensions of the EBG lattice and 2D waveguide structures fully confined quasi TE or quasi TM modes can be realised.[7] For such a structure the 2D confinement is caused by Bragg reflection, whereas the confinement in the third dimension is realised by total reflection at the wafer boundary.

The work being reported here is about the Q values and the controlled excitation of defect resonances with adjustable coupling strength. In addition to electromagnetic field simulation and experiments at around 10 GHz for the 2D TM dielectric rod structures terminated by metal

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* Corresponding author. Tel.: +49-2461-61-5722; fax: +49-2461-61-2470.

E-mail address: n.klein@fz-juelich.de (N. Klein).

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plates,[8] first simulation results for a dielectric slab structure will be shown. Such a structure could have a strong potential for future realisation in LTCC (low-temperature co-fired ceramics) or even low-loss high temperature ceramics.

Numerical simulations have been performed with the commercial electromagnetic field simulation software packages "Microwave Studio" and "MAFIA" (both from CST Computer Simulation Technology GmbH), experiments have been performed using an HP 8510 network analyser.

2. Defect modes in a 2D alumina dielectric rod structures

Localized modes in EBG structures can be used as microwave resonators. The unloaded quality factor of a resonator composed of dielectric and metal part is given by

$$\frac{1}{Q_0} = \sum_{\text{materials}} \kappa_i \tan\delta_i + \sum_{\text{surfaces}} \frac{R_{s,i}}{G_i} \tag{1}$$

with $R_{s,i}$ representing the surface resistance of the i-th metal surface and $\tan\delta_i$ the loss tangent of the i-th dielectric part. The G_i and the $\kappa_i \leqslant 1$ represent the geometric factor and the dielectric filling factors, respectively.

For a dielectric resonator, the dielecytric filling factor is generally close to 1. By confinement of the resonant mode in an air defect inside a EGB structure, the dielectric loss contribution may be reduced significantly while the mode confinement caused by Bragg-reflection can still lead to very low magnetic fields at the metal resonator walls and thus to low metal losses (high geometric factors G_i).

Fig. 1 shows examples of TM modes of a defect in an EBG lattice of alumina rods ($\varepsilon_r = 9.6$) with a radius of 2.16 mm and a lattice constant of 7.2 mm. The extended defect has been generated by removing $1+6+12=19$ rods, thereby forming a hexagonal shaped air cavity with a width of eight lattice periods. Employing the MAFIA eigenmode solver we could identify six defect related eigenmodes within the lowest three bandgaps of the EBG structure. The κ-values ($\kappa = \Sigma\kappa_i$) of the dielectric

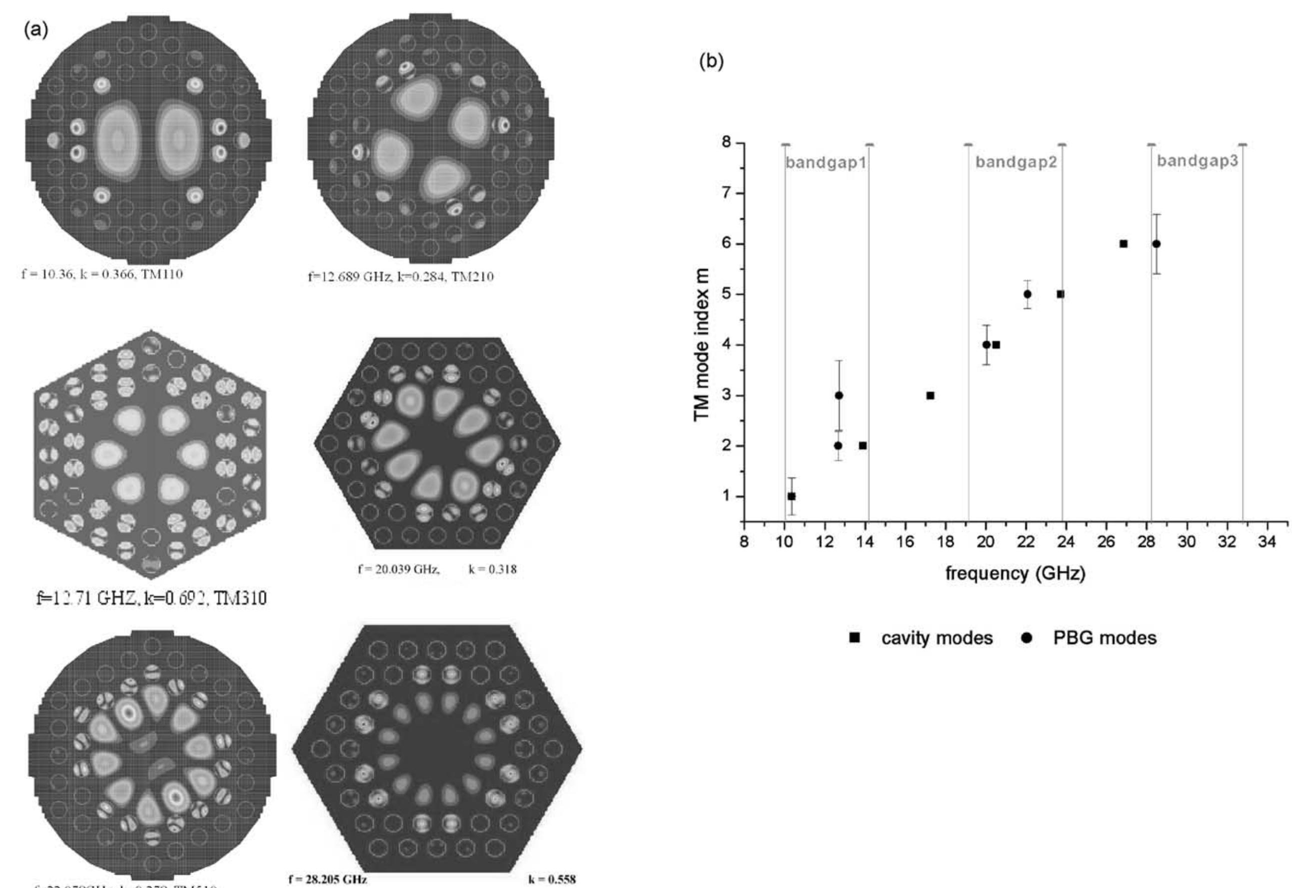

Fig. 1. Simulated electric field energy (a) of TM modes in an extended defect in a hexagonal lattice of alumina rods ($\varepsilon_r = 10$) of radius 2.16 mm with a lattice constant of 7.2 mm. The extended defect has been generated by removing $1+6+12=19$ rods, thereby forming a hexagonal shaped air cavity with a width of eight lattice periods. (b) shows the azimuthal mode index m (corresponding to half the number of intensity maxima along the circumference) as a function of frequency for the EBG defect modes in comparison to TM_{m10} modes of a cylindrically shaped cavity resonator. The error bars indicate the dielectric filling factors κ_i of the different modes.

rods were calculated by integration over the calculated electric field energy distribution depicted in Fig. 1a. The calculated values between 0.28 and 0.7 indicate that defect modes exhibit a significantly lower level of dielectric losses than typical dielectric resonator modes. Fig. 1b shows the azimuthal mode index m (corresponding to half the number of intensity maxima along the circumference) as a function of frequency for the EBG defect modes in comparison to TM_{m10} modes of a cylindrically shaped cavity resonator. The diameter of the cavity resonator (about the diameter of the defect) was selected to achieve the best possible agreement with the defect resonance data. It can be seen that defect modes with a corresponding cavity mode frequency outside a band gap are pulled into the band gaps (modes TM_{310}, TM_{610}). According to the calculated κ values, those ‘‘pulled’’ modes exhibit relatively high dielectric filling factors due to a non-ideal adjustment of the field distribution to the defect size. These results indicate, that the dielectric Q factor of defect resonances can be optimised by geometrical means.

The utilisation of defect modes in integrated circuits consisting of EBG line defect waveguides depends strongly on the availability of schemes for their controlled excitation. In Ref. 8 we have discussed the impedance matching properties of a transition from a conventional waveguide to a one and three row line defect in a hexagonal EBG lattice. In addition, it was shown that a local modification of certain lattice elements between a line defect waveguide and an extended defect resonator allows for the adjustment of resonator coupling.

Fig. 2a shows a schematic view of an extended defect (4) coupled by external waveguides (2) via line defects. The coupling can be adjusted by varying the diameter of the marked rod elements (5). Fig. 2b show a photograph of the assembly including the copper housing (1) and the alumina rod lattice (3). The simulated results of $|S_{21}|$ versus frequency as a function of the diameter of the rods

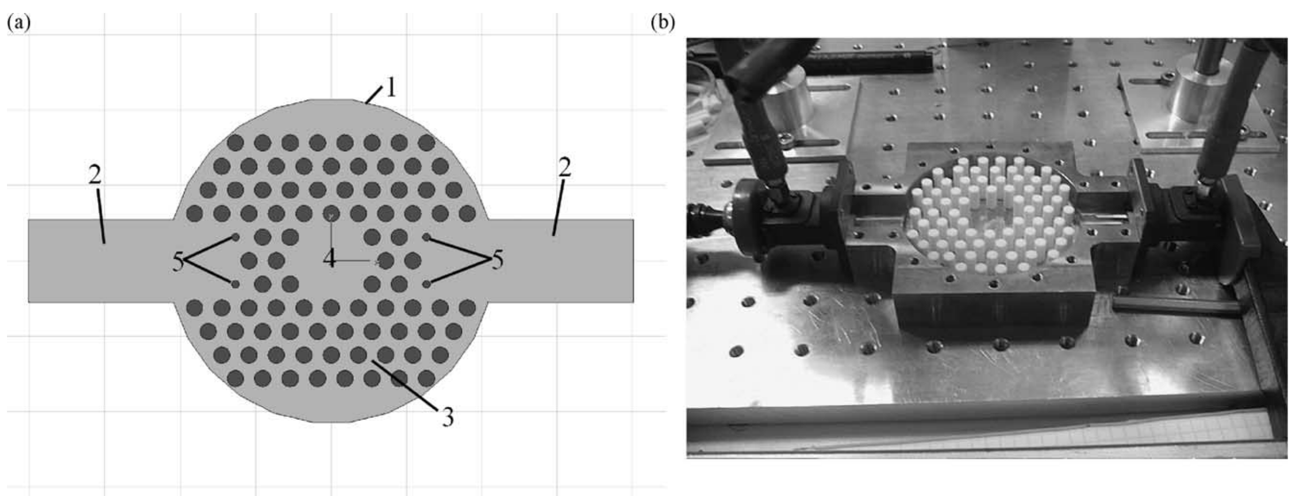

Fig. 2. Schematic view (a) of an extended defect (4) excited by external waveguides (2) via line defects. The coupling can be adjusted by varying the diameter of the marked rod elements (5). (b) shows a photograph of the assembly including the copper housing (1) and the alumina rod lattice (3).

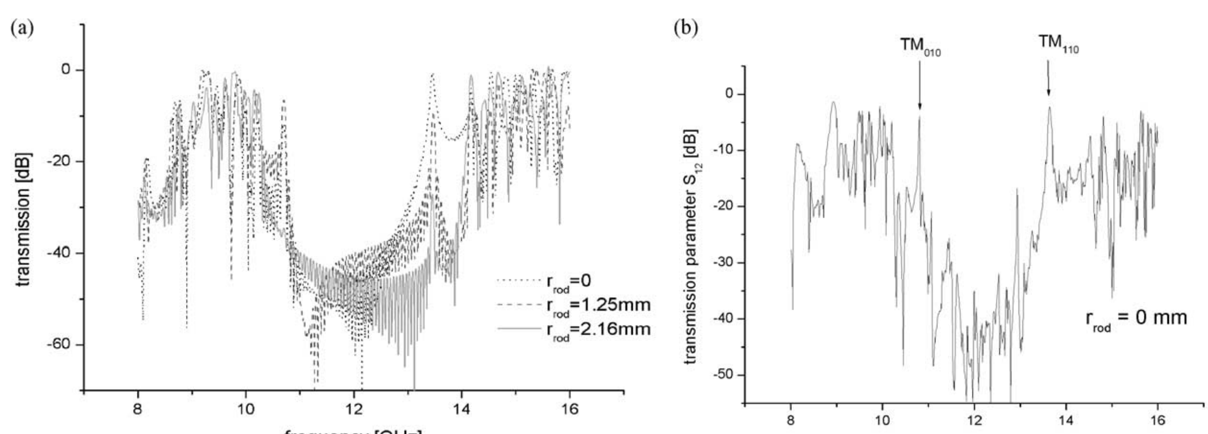

Fig. 3. Simulated results of $|S_{21}|$ versus frequency as a function of the diameter of the rods marked in (a) and experimental results for removed rods (b).

marked in Fig. 2a indicate that the coupling strength to defect modes within the gap (TM_{010}, TM_{110}) can be varied strongly (Fig. 3a,b). As discussed in Ref. 8, there is still a strong discrepancy between the measured (≈4000) and calculated (≈12,000) unloaded quality factors. In spite of this, our results demonstrate the controlled operation of EBG defect resonances as transmission line resonator with insertion loss values at resonance being typical for possible feedback oscillator operation.

3. Coupling to and transmission through a 3D confined waveguide in a dielectric slab

The 2D TM structures discussed in Section 2 are composed of single lattice elements, for which an implementation in any integrated ceramic layer technology may be difficult. As an alternative, we have employed 2D EBG modes in a dielectric slab of finite height, which is suspended in air. The existence of confined modes in particular line defects in dielectric slabs has been reported quite recently.[7] Fig. 4 shows the geometry employed for our simulation. The structure represents a transition from a metallic waveguide filled with dielectric to a line defect mode in an air-suspended dielectric slab ($\varepsilon_r = 5.8$) of finite thickness of 0.5 mm. The 2D EBG structure is a hexagonal lattice of metallic rods of diameter 0.3 mm separated by 0.5 mm. Such a structure could be prepared by LTCC ceramics. One advantage of metal rather than dielectric rods is that the lower electromagnetic band edge is determined by the inductivities and capacities formed by the combination of metallic and dielectric parts according to

$$\omega_l \approx 1/\sqrt{LC}$$

and can therefore approach zero for large capacities.[9,10]

The width of the dielectric slab waveguide (region without lattice elements) and the slab thickness was chosen such that the cut-off frequency is below 70 GHz and that the guiding mode remains confined in the direction perpendicular to the slab plane by total reflection. Fig. 5 a shows the simulated transmission and reflection amplitudes for the structure and the calculated distribution of electric field for a cross section perpendicular to the direction of propagation in the defect guide at a frequency of 110 GHz (Fig. 5b). The insertion loss was found to be less than −1 dB for 115–125 GHz and less than 2 dB for 90–140 GHz. These results indicate reasonable broadband transmission behaviour and impedance matching to external waveguide ports. The field distribution depicted in Fig. 5b visualises the in-plane field confinement by Bragg reflection and the out-off-plane confinement by total reflection.

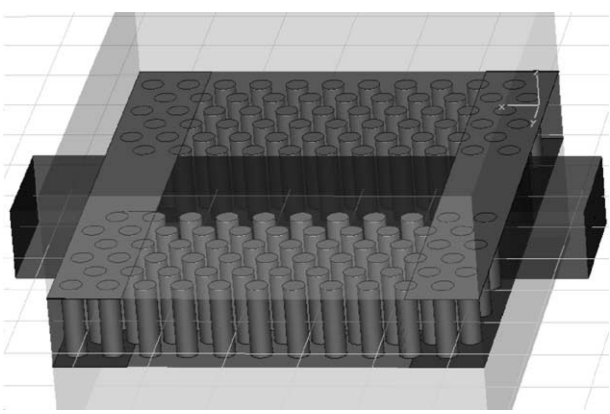

Fig. 4. Simulation geometry for coupling from a dielectric filled metallic waveguide to a line defect mode in an air-suspended dielectric slab of ($\varepsilon_r = 5.8$) of finite thickness of 0.5 mm. The 2D EBG structure is a hexagonal lattice of metallic rods of diameter 0.3 mm separated by 0.5 mm.

4. Conclusion

The Q factors of resonant modes in extended defects of a hexagonal EGB lattice of dielectric rods have been analysed. We have identified modes with a dielectric filling factor of less than 30%. In addition, we have demonstrated a defined excitation of such defect

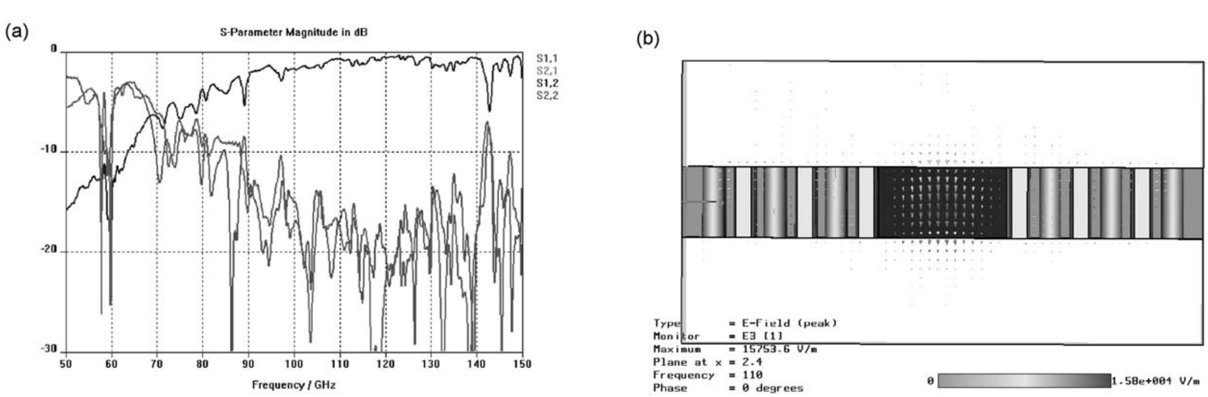

Fig. 5. Simulated transmission and reflection amplitudes for (a) the structure shown in Fig. 4 and calculated distribution of electric field for a cross section perpendicular to the direction of propagation in the defect guide at a frequency of 110 GHz (b).

resonances. As a step toward a novel millimetre wave integrated circuit technology, we have demonstrated the defined excitation of 3D confined modes of a line defect in an air-suspended a dielectric slab by an external waveguide.

Our findings represent an important step towards the practical use of EBG structures as millimetre wave circuits. Possible applications are integrated oscillator circuits with a defect-type transmission line resonator representing the frequency and phase-noise determining circuit element. Such structures could be realised by current ceramics technologies.

Acknowledgements

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References

1. Joannopoulos, J. D., Meade, R. D. and Winn, J. N., *Photonic Crystals*. Princeton University Press, Princeton, NJ, 1995.
2. Meade, R. D., Brommer, K. D., Rappe, A. M. and Joannopoulos, J. D., Photonic bound states in periodic dielectric materials. *Phys. Rev. B*, 1991, **44**, 13772.
3. Bayindir, M., Temelkuran, B. and Ozbay, E., Photonic-crystal based bema splitters. *Appl. Phys. Lett.*, 2000, **77**, 3902.
4. Mekis, A., Fan, S. and Joannopoulos, J. D., Bound states in photonic crystal waveguides and waveguide bends. *Phys. Rev. B*, 1998, **58**, 4809.
5. Lin, S., Chow, E., Hietala, V., Villeneuve, P. R. and Joannopoulos, J. D., Experimental demonstration of guiding and bending of electromagnetic waves in a photonic crystal. *Science*, 1998, **282**, 274.
6. Plihal, M. and Maradudin, A. A., Photonic band structure of two-dimensional systems: the triangular lattice. *Phys. Rev. B*, 1991, **44**, 8565.
7. Johnson, S. G. *et al.*, Linear waveguides in photonic crystal slabs. *Phys. Rev. B*, 2000, **62**, 8212;
   Sondergard, T. and Lavrinenko, A., Large-bandwidth planar photonic crystal waveguides. *Optics Comm.*, 2002, **203**, 263.
8. Schuster, M. and Klein, N. Controlled excitation of electromagnetic bandgap line- and point defect modes at microwave frequencies. *J. Appl. Phys.*, 2003, **93**, 3182.
9. Sievenpiper, D. F. and Yablonovitch, E. *et al.*, 3D metallo-dielectric photonic crystals with strong capactive coupling between metallic islands. *Phys. Rev. Letters*, 1998, **80**, 2829.
10. Gadot, F. *et al.*, High transmission defect modes in two dimensional metallic photonic crystals. *J. Appl. Phys.*, 1999, **85**, 8499.