Hollow-core resonator based on out-of-plane 2D photonic band-gap crystal cladding

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Abstract— **we report on the demonstration of a resonator based on electromagnetic field confinement in a hollow-core by an out-of-plane 2D photonic band-gap (PBG) crystal cladding. The resonator is designed to concentrate the energy within an air region in the center of the resonator and away from the cavity walls to minimize conductor losses. In contrast with in-plane 2D PBG crystal devices, the PBG crystal studied here is perpendicular to the propagation plane. A resonator was constructed with silica rods to prove the concept at frequencies around 30GHz.**

I. INTRODUCTION

Low noise oscillators require high-Q resonators for low phase noise and high stability. The Q-factor of a standard dielectric resonator is usually limited by the dielectric loss tangent of the material. One way of beating the loss-tangent limit is by confining the electromagnetic field in a hollow-core with the help of a photonic band-gap (PBG) cladding. Highest Q-factor (300,000) has been obtained by a hollow-core resonator with one-layer structure (1D crystal) that confines the mode mainly in the central air region through Bragg reflection [1-2]. In contrast with in-plane photonic crystal (PhC) devices, in such PBG cladding, the structured crystal is perpendicular (out-of-plane) to the propagation plan. Out-of-plan PBG structures have been studied since 1978 in optical fiber domain [3-4], and have led to hollow-core photonic crystal fibers that have become the most advanced manifestation of 2D PBG structures, enabling the guidance of light in a hollow core with low attenuation on kilometer-length scales [5]. Out-of-plane crystal acts on the transverse component of the field (wave vector k_T) leading to a crystal pitch longer than the wavelength (since $k_T < k_0$) and therefore to a weaker sensitivity of the confined field to fabrication imperfections. This scale factor is thus of primary importance for building high Q resonators at microwave to millimeter wave frequencies. In this communication, we report what is to our knowledge the first demonstration of a hollow-core resonator based on out-of-plan 2D PBG crystal cladding.

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II. RESONATOR DESIGN

The resonator we investigate is composed of an array of dielectric rods (in air) with a triangular lattice that is sandwiched between two copper plates (Fig. 1). The hollow-core is obtained by removing one or several rods in the centre of the lattice. Within specific wavelength and effective index ranges depending on the opto-geometrical parameters of the crystal (rod diameter (d) and permittivity, crystal pitch (Λ)), rods in the cladding act as coupled resonating-waveguides [6]. As a result allowed and forbidden photonic bands are formed within the mode spectrum of the photonic crystal cladding (Fig.2). A computed intensity picture of a mode of an allowed band is shown in the inset A of Fig. 2. These band-gaps can extend to effective values below the lowest refractive index within the photonic crystal (unity for air/silica cladding), so field trapping is then possible by introducing a defect area of low refractive index in the photonic crystal, provided that the defect supports guided mode within the forbidden band (i.e. band-gap).

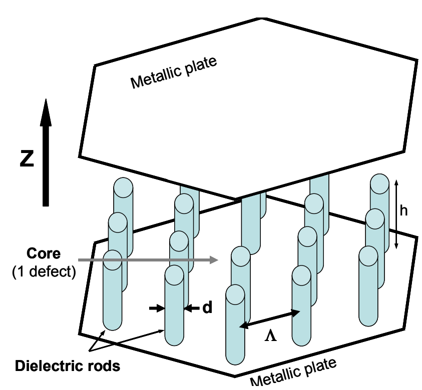

Fig. 1. Schematic of the resonator structure.

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The effective index is the propagation constant (here, projection of the wave vector along axis z) divided by the wave number. The curve inside the bandgap (Fig. 2) corresponds to the effective index curve of the fundamental mode HE_{11} confined by the PBG effect in a hollow-core, formed by removing one dielectric rod in the center of the 2D crystal. A computed intensity picture of this mode is shown in the inset B of Fig. 2. The field is confined by the crystal in the plan perpendicular to the propagation axis; *z*. Confinement along the propagation axis is achieved by a Fabry-Perot cavity composed of two copper plates as shown in Fig. 1, which is not optimized for high Q. It is used to prove the principle of resonance based on out-of-plane 2D PBG crystal and to study its behavior at microwave frequencies.

III. EXPERIMENTAL RESULTS

The PBG crystal of the fabricated resonator is composed of four rings of silica rods (d = 2.5mm, Λ = 12.5mm). These rods are fabricated with the help of the optical fiber fabrication facilities at XLIM research institute. A silica bar (D~ 25mm) is drawn to rods with diameter accuracy better than 1%. The parameters of the PBG crystal (d and Λ) are chosen to induce a PBG confinement in a hollow-core in the frequency range from 26GHz to 55GHz. The copper plate on the top is held by three micrometers adjusters to tune the spacing between both plates (i.e. cavity height) by graduations of 25.4µm. The top plate is drilled to let the silica rods protrude through. Mode excitation in the hollow-core is done with a magnetic loop to couple to the axial component of the magnetic field (H_z). A second magnetic loop is used to measure scattering parameters [S] with a vector network analyzer in transmission mode [S_{21}]. The loops are placed between both copper plates and on the sides of the PBG crystal in order to not introduce coupling losses in the quality factor measurement. The Transmission spectrum [S_{21}] is measured for resonator composed of a PBG crystal with a hollow-core formed by removing one silica rod (one defect) in the centre, and with a cavity height (h) of 5.242mm. This spectrum shown in Fig. 3 is composed by an isolated peak (centered on 30.0746GHz) with a Q-factor of 4000, and by a band of peaks at shorted frequencies.

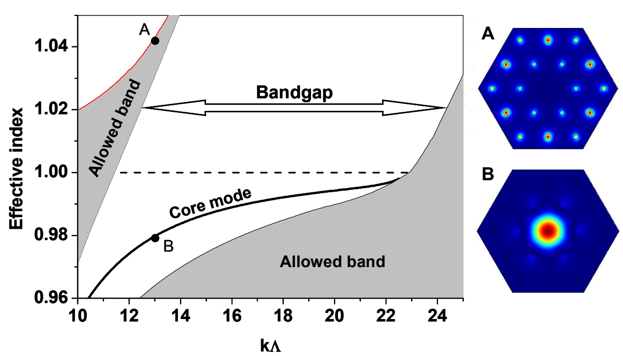

Fig. 2. Dispersion diagram of effective indices as a function of the normalized frequency kΛ of modes supported by the PBG crystal with one rod removed in the center (hollow-core). Gray areas show domains where the cladding array supports modes delimiting the band-gap (white area). Computed intensity pictures of a mode of an allowed band (A), of the fundamental mode of the hollow-core (B).

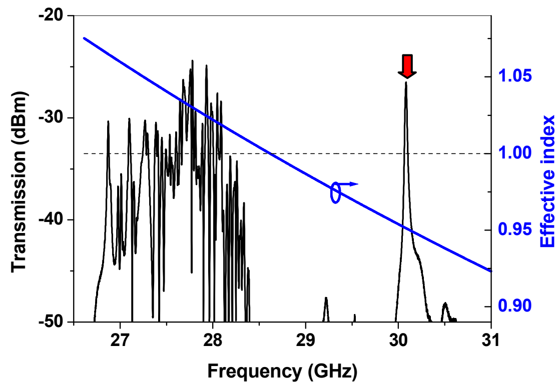

Fig. 3. Transmission spectra [S_{21}] measured with a vector network analyzer of a resonator composed of a PBG crystal with one single silica rod in the center, which one is surrounded by four rings of silica rods. Effective index of the mode fulfilling the resonance condition of a Fabry-Perot cavity is plotted versus frequency in each spectrum in bold.

Confinement of an electromagnetic field in a hollow-core is achieved when its effective index (n_{eff}) is below unity. For this resonator structure, the effective index is easily deduced to the resonance relation of a Fabry-Perot cavity:

$$n_{eff}\left(\frac{2\pi f_r}{c}\right)h = \pi$$

Here h is the cavity height (h = 5.242mm) and f_r the resonant frequency. To understand the nature of theses peaks, the evolution of the effective index versus frequency is superposed in the figure. The effective index of mode related to the isolated peak is below unity (n_{eff} = 0.95) indicating that the electromagnetic field of this mode is confined in air by the PBG crystal.

In order to determine the location of the confined electromagnetic field in the PBG crystal, another rod is removed to form a larger asymmetric hollow-core (see inset of Fig. 4). The [S_{21}] measured spectrum is very different to the spectrum measured for a single defect hollow-core.

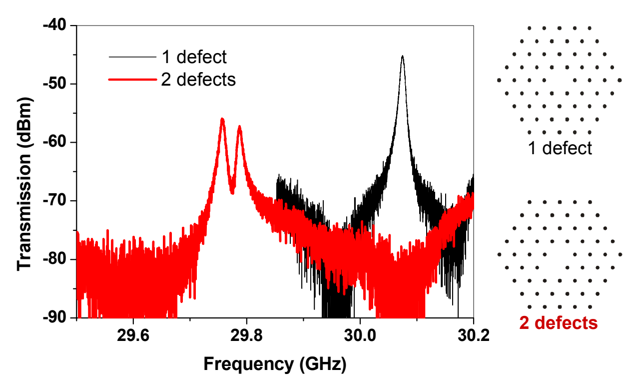

Fig. 4. Transmission spectra [S_{21}] measured with a vector network analyzer of a resonator composed of PBG crystal with one or two silica rods removed in the center. Insets show schematic representations of the PBG crystal topologies studied.

The spectrum nearby 30 GHz is composed of two resonant peaks centered at shorted frequencies. This behavior contrast with the negligible shift of the resonant peak induced when a rod is removed far from the hollow-core, in an external ring. This experiment illustrates a much stronger confinement of the electromagnetic field in the hollow-core than in the crystal cladding. This is in good agreement with the field expansion of the expected mode, as shown in the inset of Fig. 2.

These features prove the confinement of the mode related to the isolated peak (Fig. 3) in the hollow-core by the PBG crystal. This spectrum is also composed by a band of peaks at shorted frequencies. The effective indices of the modes related with the band of peaks are just above unity (Fig. 3) while the one of the isolated peak is well below it. These features suggest that the band of peaks is not due to field confinement in the hollow core. To investigate the nature of these peaks, transmission spectra [S_{21}] are recorded at different cavity heights (Fig.5). As expected with the Fabry-Perot resonance relation, peaks shift to higher frequencies with the decrease of the cavity height. This is accompanied by shrinkage of the band of peaks and increase of the gap between the band and the isolated peak. The evolution of this band of peaks is similar to the allowed band of modes (cladding modes) that delimits the PBG band in the short frequency edge (Fig. 2). These peaks are thus induced by cladding modes supported by the PBG crystal outside the PBG band.

To push further the investigation on the PBG crystal behavior, effective indices of the modes supported by the PBG crystal are simulated with the help of commercial software (COMSOL) based on finite element method.
Permittivity of the silica rods is measured from a sample of the silica bar used. The measurement method is based on microwave resonator. A permittivity of 3.787 is deduced by retro-simulation from the measurement of the frequency of the resonant peak associated to the transverse electric mode TE_{011} confined in the silica bar sample, which one is placed inside a specially designed resonator cavity. Further measurements are in progress with the conventional characterization method based on whispering gallery modes [7]. The retro-simulation is done with the method of lines based on a rigorous analysis of the electromagnetic field [8-9]. The simulated effective indices of the modes confined in the hollow-core mode and in the crystal cladding (rods) are plotted (black dots) in Fig. 6.

The effective index of the mode related with the isolated peak deduced from the resonance relation of a Fabry-Perot cavity is plotted (lozenges) versus frequency in Fig. 6. The evolution of the effective index of this mode confined in the hollow-core is close to the simulated one confirming the field confinement in the hollow-core by the PBG crystal. The discrepancy between simulated and measured curves is about 2%. This difference is equal to an uncertainty of 100µm on the measurement of the cavity height for a resonant peak at 34GHz (h = 4.46mm). This uncertainty is large; the discrepancy is thus not only due to measurement uncertainty of the cavity height.

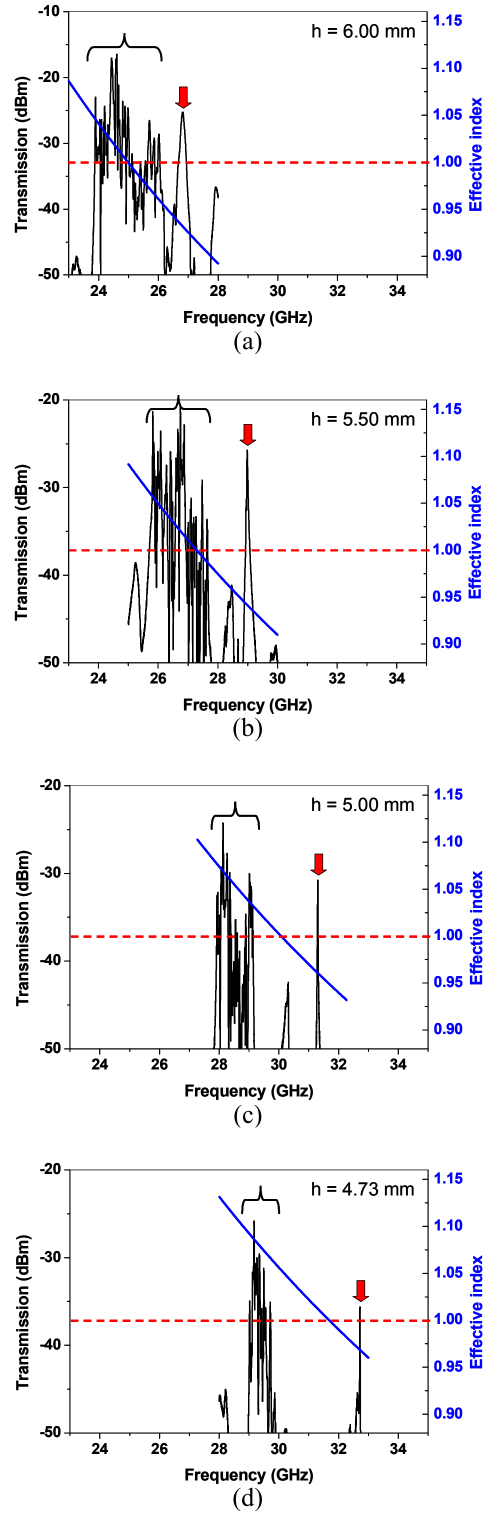

Fig. 5. Transmission spectra [S_{21}] measured with a vector network analyzer of a resonator composed of a PBG crystal with one single silica rod in the center, which one is surrounded by four rings of silica rods. Transmission spectra [S_{21}] are recorded for a cavity height of 6.00mm (a), 5.50mm (b), 5.00mm (c) and 4.73mm (d). Effective index of the mode fulfilling the resonance condition of a Fabry-Perot cavity is plotted versus frequency in each spectrum in bold.

The simulated effective index curve is obtained from the modeling of the PBG crystal only. The modeling of the real structure (with the copper plates) requires a 3D simulation that has not yet been implemented. The experimental curve is deduced from the resonant condition of the Fabry-Perot cavity formed by the copper plates. However in this relation perfect plates are considered, while in the experiment the top plate is drilled through, modifying probably the effective cavity height. To study this assumption, the central hole in the top plate is roughly filled with a metallic rod. The effective index curve measured in this configuration is plotted (circle) in Fig.6. The mismatch with the simulated curve falls to 1.3 %. A better agreement might be obtained for resonator with a fixed cavity height since the copper plate on the top does not need to be drilled through.

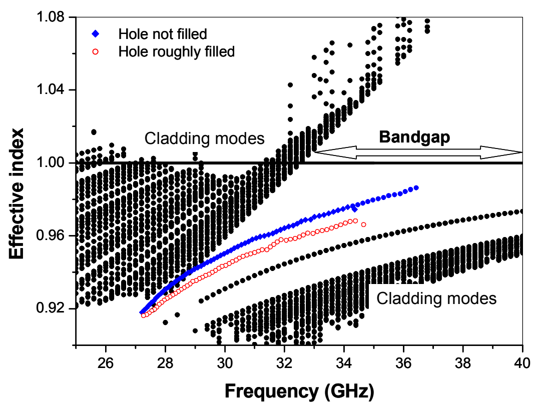

Fig. 6. Simulated dispersion diagram of effective indices (black dots) as a function of the frequency of modes supported by the PBG crystal with one rod removed in the center (hollow-core). Effective index curves deduced from measures, of the mode confined in the hollow-core with the central hole of the copper plate on the top unfilled (lozenge) or roughly filled with a metallic rod (circle).

Based on simulations and on different experiments, we have successfully demonstrated the first realization of a hollow-core resonator based on out-of-plan 2D PBG crystal cladding. Following this demonstration of principle, the Q-factor of this type of resonator will be improved by using a low-loss dielectric such as alumina.

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