Highly tunable photonic crystal filter for the terahertz range

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By use of an incipient ferroelectric, $SrTiO_3$, as a defect material inserted into a periodic structure of alternating layers of quartz and high-permittivity ceramic, thermal tuning of a single defect mode over the entire lowest forbidden band was obtained. The tunability of this compact structure reached 60%. © 2005 Optical Society of America

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Photonic crystals (PCs) are periodic structures belonging to a new class of artificial materials that allow one to manipulate the flow of light.[1] Their key feature is a frequency region in which the propagation of any electromagnetic radiation is prohibited.[2,3] Even more interesting are PCs with broken periodicity, since defects in otherwise periodic PCs cause highly localized defect modes[4] that are utilized for construction of filters with an exceptionally narrow transmission band,[5] resonant cavities,[6] and waveguides.[7] These PCs also play an important role in nonlinear optics because of their strong field localization and related enhancement of nonlinear phenomena.[8] To extend the versatility and application of PCs with defects, it is desirable to tune the defect modes. The resulting devices are interesting for optical communications and in spectroscopic applications.

Control of the properties of PCs by external parameters has attracted much attention. Several studies have concentrated on tuning the forbidden bands,[9–11] on light switching,[12,13] and on tuning defect modes.[14,15] Most of those efforts were devoted to the microwave and the optical spectral ranges, whereas only a few works have dealt with the terahertz (THz) region.[16–18] However, this region is of particular interest: besides its fundamental spectroscopic applications, this region is intensively exploited in view of novel imaging techniques in medicine and security and for applications in atmospheric remote sensing and astronomy.[19,20]

In this Letter we demonstrate a defect mode in a one-dimensional PC that can be tuned in frequency by 60%, i.e., over the entire lowest forbidden band. The tunability originates from strong temperature dependence of the dielectric function of an incipient ferroelectric crystal ($SrTiO_3$) used as the defect material. The proposed structure does not include air layers and forms an easy-to-fabricate compact and rigid tunable filter.

The investigated structure can be considered a one-dimensional PC with a twin defect: a defect layer is symmetrically enclosed between two Bragg mirrors. Let us denote n_L and n_H ($n_L < n_H$) as the refractive indices of the two alternating layers forming the Bragg reflectors and n_D as the refractive index of the defect layer. Maximum tunability, i.e., tuning capability over the entire forbidden band, is achieved if the optical thickness of the defect can be changed by an amount comparable to the central wavelength of that forbidden band.[21] However, this optical thickness must be kept sufficiently small to prevent more than one defect mode from appearing in the forbidden band. Thus the material chosen for the defect should exhibit a large change of dielectric properties, and its losses should be as low as possible to simultaneously yield high peak transmission and a good quality factor. Promising candidates with these properties are incipient ferroelectric crystals with a perovskite structure, including $SrTiO_3$, $KTaO_3$, and $CaTiO_3$, the dielectric properties of which are easily varied over a large range by changing temperature.[22] Here we use a $SrTiO_3$ single crystal that satisfies the requirements above quite well. We measured its permittivity and loss tangent by use of time-domain THz spectroscopy.[23] The results are shown in the inset of Fig. 2, below: the change in permittivity reaches nearly a factor of 7 from 75 to 300 K, whereas the loss tangent remains lower than 0.03 in the given temperature range.

The design of the structure enclosing the defect is also important for the performance of the filter. (i) The higher the reflectivity of the Bragg mirrors is, the narrower the defect mode and the higher the effective losses in the defect.[24] Consequently, Bragg mirrors with moderately high reflectivity constitute a good compromise between the high peak transmission and the width of the filter passband.[25] (ii) In Bragg

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mirrors composed of two types of alternating layer, the width of the first forbidden band is maximal when the optical thicknesses of the layers are equal.[26] (iii) The refractive index of $SrTiO_3$ is rather high ($n_D \gg n_L, n_H$). In such a case the widest tunability is achieved when the defect is surrounded by n_L layers (those with a lower refractive index).[21,25] These conditions allow us to select the sequence and geometry of layers used in our structure.

Typically, most PCs in the microwave and THz ranges use air as the medium with the low refractive index. However, such structures can often be very fragile. To overcome this problem we used crystalline quartz for the layers adjacent to the defect ($n_L \sim 2.1$) and a high-permittivity ceramic (undoped CeO_2, $n_H \sim 4.8$) for the other layers. This material has low losses in the THz range, and its permittivity exhibits only a very small temperature dependence.[27] The ratio of refractive indices is $\sim$2.3, which is even slightly higher than that of a structure composed of a sequence of crystalline quartz and air layers.

The investigated structure was constructed as follows: each Bragg mirror was fabricated from three crystalline quartz wafers (thickness 230 μm) interleaved with two layers of CeO_2 ceramic (thickness 100 μm). The Bragg mirrors were fixed by drops of glue at the edges. The defect was made from a 41-μm-thick $SrTiO_3$ single crystal. The surfaces of all the constituent layers were optical quality. The entire structure was enclosed between two metallic apertures and tightened with small screws.

The transmittance of the sample was measured with a coherent source spectrometer[28] in the frequency range 67–260 GHz and for temperatures from 75 to 295 K. The room-temperature transmittance of the structure is shown in Fig. 1(a) along with the result of a numerical simulation based on transfer matrices and an analytical fit of the dielectric properties of $SrTiO_3$ shown in the inset of Fig. 2. The lowest forbidden band spreads from 90 to 220 GHz; one can also identify a single defect mode at $\sim$185 GHz. Figure 1(b) illustrates the frequency tuning of the defect mode with temperature for three different temperatures. Finally, in Fig. 2, the defect mode frequency is plotted versus temperature over the whole temperature range 100–300 K. The defect mode can be tuned from 185 GHz at room temperature down to 100 GHz at 100 K. The relative tunability, calculated as the tuning range over the central frequency, thus reaches an outstanding value of 60%. At the same time, the peak transmission always exceeds -9 dB and the full width at half-maximum of the defect mode varies from 2.0 to 4.5 GHz. The small systematic shift between the measured and the numerically calculated frequencies of the defect mode [Figs. 1(a) and 2] is attributed to the uncertainty of the structural parameters of the PC.

The demonstrated tuning range can possibly be further extended if a slightly modified structure is used. The factor limiting our actual tuning range is the width of the forbidden band, which can be enhanced in multilayered structures by an increase in the ratio of refractive indices n_H/n_L.[26] For instance, plastics such as TPX or Mylar can serve as n_L materials.[28] Then, in the temperature range 85–400 K it should be possible to achieve a tunability of 80% (90–210 GHz).

Thermal control of PCs may be useful for certain applications, such as prefiltering in radioastronomy, for which its slowness is not a drawback. However, optical or electrical control is desirable for applications

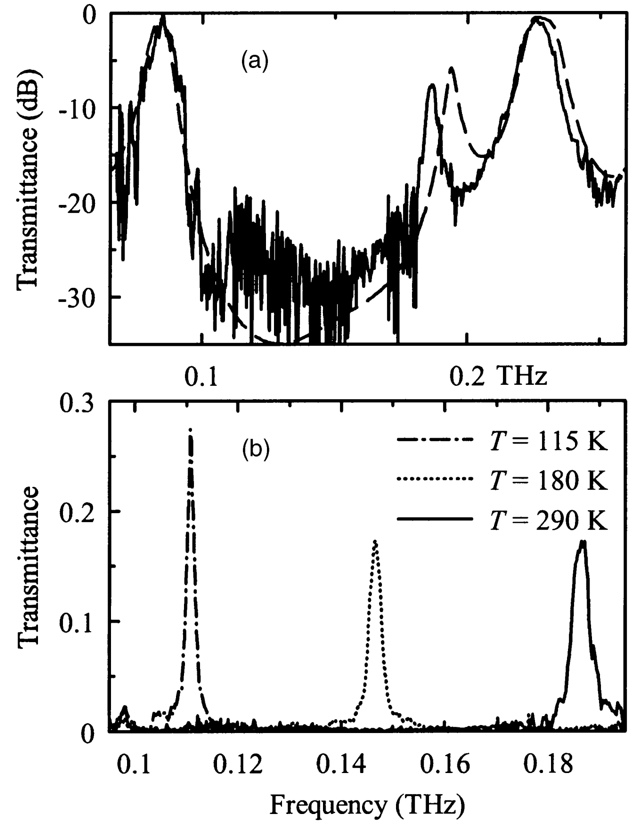

Fig. 1. Power transmittance of the investigated structure. (a) Room temperature: solid curve, experiment; dashed curve, numerical simulation. (b) Typical spectra experimentally obtained in the tuning range.

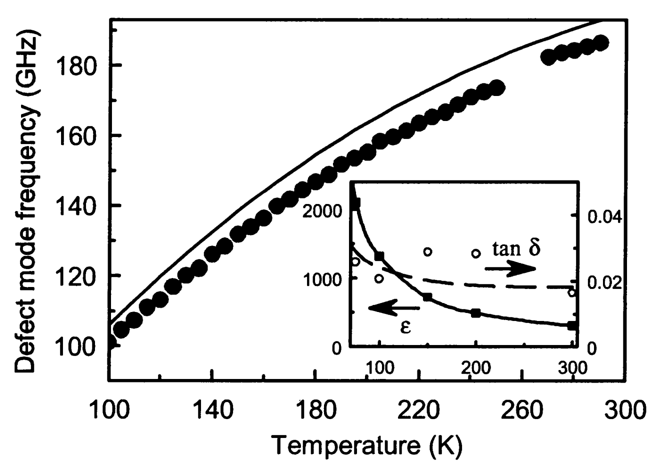

Fig. 2. Tuning curve of the defect mode. Filled circles, measured defect frequency; solid curve, results of a numerical simulation. Inset, temperature dependence of the permittivity (ϵ) and the loss tangent ($\tan\delta$) of a $SrTiO_3$ single crystal at 0.2 THz measured by time-domain THz spectroscopy. Points, measured values; curves, analytical fits of the data.

requiring a high operating speed. This work marks a significant step toward such control, as the influence of an applied electric field on the dielectric properties of ferroelectric crystals is very similar to that of temperature.[29]

The investigated structure was designed to operate in the sub-THz range. Just by applying the scaling laws,[3] one can construct an analogous structure with appropriately scaled layer thicknesses for the gigahertz range. The real properties of such a structure may be effectively modified by a possible dielectric dispersion of the constituent materials. However, both quartz and CeO_2 show virtually no dispersion of permittivity and negligible losses in the gigahertz and sub-THz ranges.[27,28] In the case of $SrTiO_3$ the loss tangent scales nearly linearly with frequency, whereas its permittivity remains practically constant.[30] Consequently, the relative tuning range remains unaffected for a structure designed for lower frequencies, whereas the peak transmission is expected to increase considerably. For example, scaling the investigated structure by a factor of 10 would lead to a tuning range of 10.0–18.5 GHz with a peak transmission reaching −1.5 dB. Scaling by only a factor of 3 would lead to a peak transmission greater than −4.6 dB.

In summary, we have demonstrated outstanding tunability of a one-dimensional photonic crystal filter. By controlling the temperature of the structure in the range 100–300 K, we tuned a single defect mode over the entire lowest forbidden band, yielding a relative tunability of 60%.

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