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Thermally tunable filter for terahertz range based on a one-dimensional photonic crystal with a defect

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A high-quality smart filter for terahertz range with relative tunability reaching 20% has been demonstrated. The filter is based on a narrow transmission band, which originates from a defect mode that appears due to insertion of a single crystal of $KTaO_3$ into otherwise periodic one-dimensional photonic crystal. Frequencies of defect modes are controlled by the refractive index of the defect: their high tunability is achieved by the strong temperature dependence of the dielectric properties of $KTaO_3$. The low losses of $KTaO_3$ lead to a high peak transmission of the filter. Influence of the defect losses on the properties of the filter is also discussed. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1787623]

Photonic crystals (PCs) are periodic structures, which can exhibit frequency regions in which the propagation of electromagnetic waves is forbidden.[1] Breaking the periodicity of a PC leads to the creation of extremely narrow defect modes in the forbidden bands.[2] There are various potential applications based on the unique properties of PCs, such as inhibition of spontaneous emission, light localization, and enhancement of nonlinear phenomena.[3,4] The use of PCs with a defect for high-quality frequency filtering in spectroscopy or in communication devices is a straightforward and potentially very promising application. In order to extend its scope and versatility, it is necessary to find a simple mechanism for the tunability. While several studies deal with the tunability of forbidden bands[5,6] or switching of defect modes,[7] the tunability of defect modes still remains a topic much less explored.[8,9]

The terahertz (THz) spectral domain has been a very active field of research for the last two decades owing to the development of time-domain THz spectroscopy (TDTS).[10] This method allows fast and reliable phase-sensitive measurements without requiring any calibration as it is the case when using vectorial network analyzers. Consequently, in addition to the well-established spectroscopic applications,[11,12] it can be used for full characterization of PCs (Ref. 13) as well as for THz imaging and tomography.[12,14]

The THz region is of particular interest regarding the design, characterization, and applications of photonic structures. The appropriate PCs have submillimeter lattice period and thus can be fabricated relatively easily.[15,16] The THz spectral range is characteristic for rotational transitions of many gas species and it thus constitutes a unique source of information for the analytical chemistry of gases with applications in atmospheric remote sensing and in astronomy:[17] observation of vibrational and rotational transitions of molecules makes it possible to detect a wide variety of molecules in interstellar clouds, for example.[18] The dynamic range of existing detectors could be increased if high-quality prefiltering is used to dramatically reduce the noise bandwidth. The tunability would finally allow a simple selection of the investigated spectral range.

PCs (Ref. 19) and defect modes in PCs (Ref. 16) in the THz domain have been investigated for a rather long time now. However, only a few papers deal with the tunability of defect modes.[7,13] In this paper, we report on a thermally tunable filter based on a one-dimensional PC with a defect. The related defect modes appear as very narrow transmission bands in wide regions with a suppressed transmission originating from the forbidden bands. Here we use a structure with a twinning defect, i.e., a structure consisting of two Bragg mirrors—twins—symmetrically enclosing a single-layer defect. Such a structure was theoretically investigated recently from the point of view of its tunability.[20] In order to achieve high tunability, a change of the optical thickness of the defect must be comparable to the central wavelength of the first forbidden band. However, the optical thickness of the defect must be kept small enough to avoid the presence of a large number of defect modes in each forbidden band.

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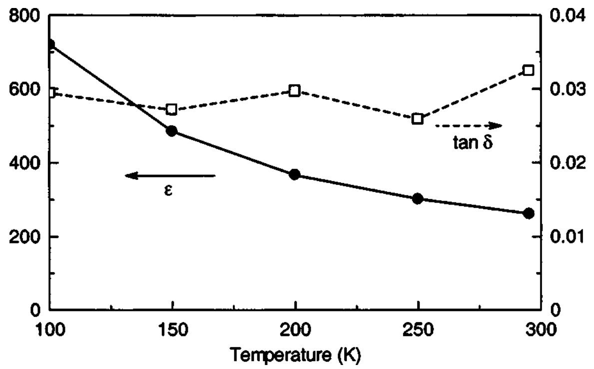

FIG. 1. Temperature dependence of permittivity ε and loss tangent tan δ of a single crystal of $KTaO_3$ measured by TDTS at 0.4 THz.

The absorption of the defect must be kept as low as possible in order to obtain a high peak transmission. These properties can be satisfied above the critical temperature of incipient ferroelectric materials with perovskite structure such as $KTaO_3$ or $CaTiO_3$.[21] In this study, we used a 65 μm thick single crystal of $KTaO_3$. Its dielectric properties in the THz region, measured using TDTS, are shown in Fig. 1: details on the measurement can be found in Ref. 22. The permittivity change of $KTaO_3$ reaches a factor of almost 3 between 100 and 300 K while the losses remain sufficiently low (loss factor tan $\delta < 0.04$) below 0.5 THz.

The investigated structure was constructed as follows. Each Bragg mirror was fabricated using three 100 μm thick wafers of quartz with a 15 mm diameter. [Its refractive index ($\sim$2.1) is constant in the THz region and the losses are negligible[23]]. The individual wafers were separated by air layers, which were created by inserting 200 μm thick silicon spacers placed near the edges of the quartz wafers. The Bragg mirrors were mechanically stabilized by drops of glue put on their edges. The $KTaO_3$ defect with a 7 mm diameter, surrounded by a 50 μm thick ring of a Mylar foil, was placed between the Bragg mirrors. Finally, the whole structure was fixed by miniature springs. In this setup we expected to minimize the curvature of the PCs caused by the stress produced during the construction or by the springs.

The transmission of the PC was measured by means of TDTS in the experimental setup described in detail in Ref. 24. Temporal scans of 150 ps duration were acquired, yielding a frequency resolution of about 7 GHz, sufficient for the characterization of our PC. The transmission spectra were measured in the temperature range from 120 to 290 K with a step of 5 K. An ultralight copper holder has been used to achieve a rapid and homogeneous thermalization of the PC. The holder contains two heating elements and temperature sensors. The temperature adjustment is obtained with a differential-integral-proportional regulation and the obtained accuracy on the regulated temperature is estimated to be better than one-tenth of kelvin. The thermal time constant of the holder-PC set is of the order of a few tens of second leading to a 2–3 min regulation time necessary to achieve the next 5 K temperature step.

The measured temperature-dependent transmission spectra are summarized in Fig. 2(a). Only the frequency region from 0.15 to 0.85 THz is displayed: the apparatus is not

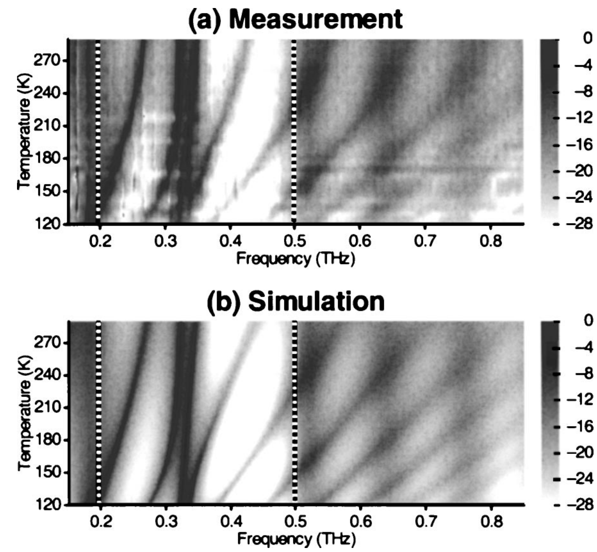

FIG. 2. Transmission (in decibels) of the PC under investigation: (a) experimentally determined data and (b) numerically simulated data. The two vertical lines indicate the edges of the first forbidden band.

enough sensitive at lower frequencies, mainly due to the presence of a 6 mm diameter diaphragm in front of the PC. On the other hand, the higher-frequency components are strongly attenuated due to high absorption in $KTaO_3$. Figure 2(b) shows the results of a numerical simulation performed using a transfer-matrix method.[20] Both measured and numerically simulated transmission curves for 280 K are shown in Fig. 3. In order to match the simulated data and the experimental results, we have considered 16 μm thick air layers on both sides of the defect. This air gap probably originates from the curvature of the PCs created during their fabrication. The remaining differences between the measured and simulated spectra are only very minor: the small amplitude mismatch takes place mainly because of the uncertainty of the defect losses entering the numerical simulation.

In Figs. 2 and 3, we can see the first forbidden band between 0.20 and 0.50 THz, where the intensity transmission is reduced by a factor exceeding 1000 in its upper part. This forbidden band is significantly wider than that of an equivalent PC without the defect (0.28–0.44 THz). This can be understood having in mind that the optical width of the de-

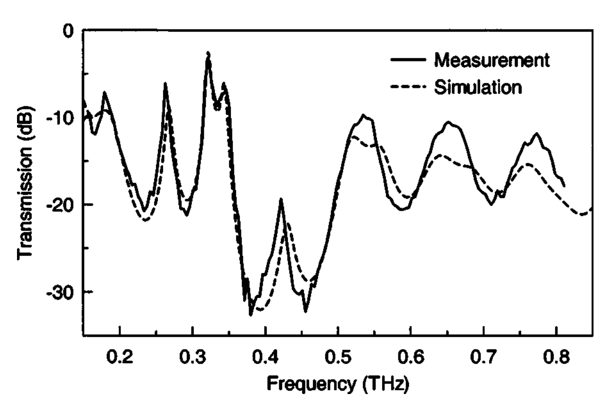

FIG. 3. Transmission (in decibels) of the PC under investigation at the temperature of 280 K. The measured data are indicated by a solid line while the numerical simulation is represented by a dashed line.

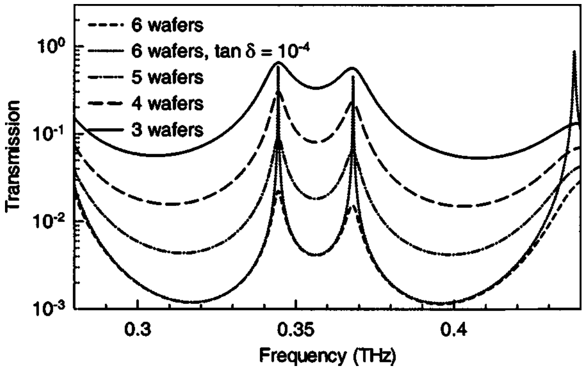

FIG. 4. Influence of the number of lattice periods of the Bragg mirrors and of the defect losses on the electric field transmission of the filter. The loss tangent is 0.03 except for the dotted curve, where 10^{-4} is used.

fect is comparable to the optical length of the rest of the PC, i.e., the band structure is affected by the insertion of the defect.

In the first forbidden band, there are five branches corresponding to distinct defect modes (Fig. 2). Except the defect mode near 340 GHz, the four other defect modes present a high tunability. The lowest branch is of major interest due to its high peak transmission (~ -6 dB). Its frequency varies from 267 GHz at 290 K down to 220 GHz at 170 K, i.e., its relative tunability reaches 20%.

The pair of defect modes appearing near the center of the forbidden band exhibits a lack of tunability in a large temperature range. An analogical behavior was reported in Ref. 20 for a high wave-impedance defect enclosed between Bragg mirrors fabricated of two alternating layers with $n_L < n_H$, where n_L is the refractive index of the layer in contact with the defect. One can easily show that the same behavior takes place in the present case where a low impedance defect ($KTaO_3$, due to its high permittivity) is in contact with the high-index layers (n_H) of the Bragg mirrors. This behavior causes a reduction of tunability to less than half of the forbidden band. Consequently, in this particular structure, the width of the forbidden band seems to be the most limiting parameter for the maximum tuning range.

Lifting this limitation will not be an easy task. The widest forbidden band arises when the optical thicknesses of the layers constituting the Bragg mirrors are the same,[25] and this requirement is already very well satisfied in our structure.

The levels appearing in the center of the forbidden band and showing low tunability can be suppressed in case low-index layers (n_L) are brought into contact with the defect, i.e., using a configuration in which air layers adjoin the defect. However, construction of such a structure would be a very delicate task.

In all cases, it is possible to enlarge the forbidden band by increasing the contrast ratio of the refractive indices of the layers constituting the Bragg mirrors. In addition, such an operation leads to further reduction of the transmission in the forbidden band. The analogy of our structure with a Fabry-Perot resonator allows us to conclude that this will also cause a narrowing of defect modes (Fig. 4). Though the defect-level narrowing as well as the suppression of the transmission in the forbidden band seem to be a further advantage from the point of view of potential applications, other effects dramatically reducing the performance of such structures take place simultaneously. The higher is the quality of the Bragg mirrors enclosing the defect (i.e., the higher are their reflection coefficients), the higher is the effective absorption of the defect.[26] Consequently, for real defect materials with small but nonvanishing losses, the peak transmission of the defect mode may dramatically decrease with increasing quality of the Bragg mirrors.

This behavior is illustrated in Fig. 4 for our structure with $KTaO_3$: the peak transmission decreases by a factor ~ 3 with each period added to both Bragg mirrors. In order to recover the high peak transmission and therefore the applicability of such a filter, the use of a highly transparent material for the defect is essential. For example, in the case of a structure fabricated of six periods on each side of the defect (instead of only 3), it would be necessary to find a material with a real part of permittivity comparable to the one of $KTaO_3$ but with the loss factor $\tan \delta < 10^{-4}$ (see the dotted curve in Fig. 4). Moreover, it would be no longer possible to characterize such structures by means of TDTS due to its low frequency resolution, and other methods such as backward-wave oscillator or vectorial network analyzer techniques would be required.[10]

A high tunability THz filter similar to the one presented in this paper would be of great interest for radio astronomy provided that the peak transmission is slightly increased and, consequently, a higher quality factor is obtained. These requirements would be satisfied using a defect material with lower losses. Indeed, a tunable high-quality prefilter based on PC put in front of the antenna of a far-infrared telescope would dramatically reduce the noise bandwidth and hence would increase the signal-to-noise ratio. Let us also notice that for this specific application, the slowness of thermal tuning is not really detrimental. Moreover, it would be possible to significantly increase the speed of thermal tuning by deposition of a resistive ring directly onto the $KTaO_3$ wafer instead of use of remote heating via the PC holder.

To summarize, we have proposed and demonstrated a thermally tunable filter for the THz range based on a PC with a defect. Its tunability reaches 20% and the peak transmission of the tunable defect mode is about −6 dB. We have also emphasized that construction of filters with higher quality (i.e., with narrower passband, lower forbidden-band transmission, and higher peak transmission) would require a material for the defect with significantly lower absorption than $KTaO_3$. In that case, such a high-quality filter with thermal tuning would constitute a prefilter of major interest for radio astronomy.

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