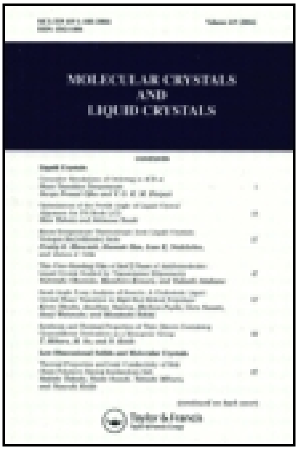

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Resonant Absorption of THz Radiation Using Nematic Liquid Crystals

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The wavelength-dependent reflectivity of linearly-polarised Terahertz (THz) radiation has been recorded from a metal grating spaced above a metal mirror by a homogeneously aligned liquid crystal layer. Clearly defined minima were observed in the spectra measured in the range 0.1–3 THz. On application of a voltage across the liquid crystal layer these resonances shift in position by up to 30 GHz due to the resulting change in the sensed refractive index. The minima are attributed to resonant absorption through the excitation of standing waves generated both across and along the liquid crystal. The mechanism responsible for this phenomenon and methods for optimising the device are discussed.

Keywords: grating; nematic; resonant absorption; spectroscopy; THz radiation

INTRODUCTION

The Terahertz (THz) range of the electromagnetic (EM) spectrum lies between the infra-red and microwave regions. Until recently this domain had been relatively unexploited due to the difficulties of generating, detecting and manipulating radiation at these frequencies. However, in the past decade, the advent of laser based sources and quantum cascade lasers which operate in this frequency range have sparked an explosion of interest in the THz region of the EM spectrum. As THz radiation has the ability to penetrate deep into organic material without the harmful effects associated with ionising radiation it has great potential for use in medical imaging and surveillance

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devices as well as in areas such as satellite communications and spectroscopy-based sub-millimetre wave astronomy.

The use of liquid crystals to control the transmission and reflection of electromagnetic radiation at wavelengths greater than those for visible radiation is still very much in its infancy. Liquid crystal devices such as Fabry Perot filters [1–4] have been effectively demonstrated at infrared wavelengths and phase shifters [5] and filters [6] for microwave applications have also been explored. However, until recently, very little work has been done on the practical uses of liquid crystals at THz frequencies. Recent studies have shown that the dielectric anisotropy of standard nematic liquid crystals such as E7 and ZLI-2293 at THz frequencies is substantial [7–9] and suitable for use in devices. However, in keeping with liquid crystal devices for optical applications most structures studied have required liquid crystal layer thicknesses that are of the order of at least the wavelength of the incident radiation (i.e. several hundred microns) which is close to or beyond the coherence length for an aligned liquid crystal.

It has recently been shown at both microwave [10] and optical [11] frequencies that electromagnetic radiation can be resonantly absorbed by a remarkably thin dielectric-core when clad with a patterned metallic layer, as shown in Figure 1. The upper surface is a metallic grating of a pitch that is significantly lower than the wavelength of the incident radiation and has a mark/space ratio of around 10. The lower plate is a continuous metal sheet of a thickness that is opaque to the incident radiation and the dielectric core that separates them is equal in thickness to around one tenth of the incident wavelength. Measurements were made of reflected intensity versus the frequency for incident radiation polarised perpendicular to the slits in both the optical

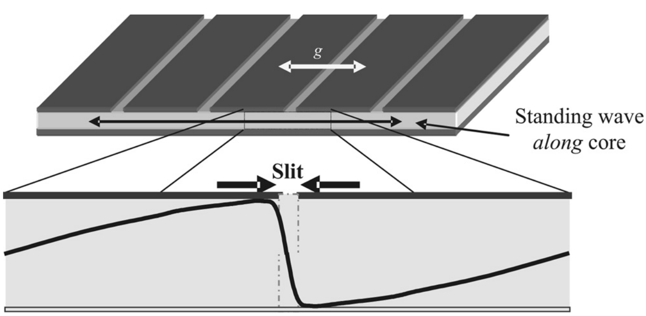

FIGURE 1 Diagram of the sub-wavelength thickness resonantly absorbing structure and the standing wave generated along the dielectric core. λ_g denotes the pitch of the grating.

and microwave studies. The resulting spectra showed a generally high reflectivity with sharp, well defined minima, the positions of which varied somewhat with the angle of incidence. Modelling using finite element software showed that at these minima the resonant absorption occurs due to a standing wave that is set up *along* the dielectric core. As shown in Figure 1, half of the wave is compressed into the region below the metallic stripes and the other half is contained within the slit width, which may be only a few percent of the wavelength in free space. Due to the extreme thinness of the samples studied, standing waves across the core were prohibited.

In the previous studies a dielectric of a fixed refractive index has been used as the core material and so the wavelength of resonant absorption could only be changed by physically altering the dimensions of the structure. However, as the position of the resonances is dictated by the refractive index of the core medium their positions can obviously be tuned by changing the refractive index of the core. This can be achieved by using an aligned nematic liquid crystal as the dielectric layer in the sample. Through the application of a voltage across the layer to control the director alignment, the effective refractive index sensed by the incident polarised radiation can be varied from the ordinary, through to the extra-ordinary value of the material.

In this study we use a structure with dimensions that have been scaled for THz frequencies. A homogeneously aligned nematic liquid crystal (E7, Merck KGaA) is used as the dielectric core medium to allow the positions of the resonant absorption of the device to be tuned by application of a voltage across the liquid crystal layer.

EXPERIMENT

A 300 μm pitch metal grating was produced on a 0.13 mm thick glass substrate by the thermal vacuum deposition of a 200 nm thick aluminium layer and then using a UV exposure and acid etch technique to create a series of aluminium stripes 200 μm wide separated by 100 μm gaps. A 15 nm layer of SiOx evaporated at a 60° angle was deposited on top of the grating structure to promote homogeneous alignment of the liquid crystal with the director perpendicular to the grating stripes. For the superstrate a 200 nm thick continuous aluminium layer was evaporated onto a 1.1 mm thick glass plate and again a 15 nm layer of SiOx was also used to produce homogeneous alignment. The device was assembled with the alignment direction on the two surfaces parallel to each other, using $\sim$100 μm thick mylar along the edges as spacers. The ends of the aluminium stripes on the

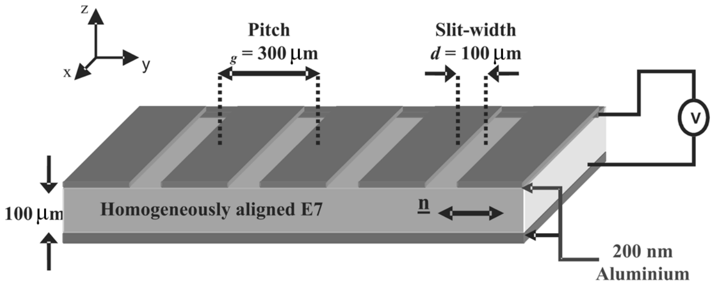

FIGURE 2 Schematic diagram of the grating structure used for the THz reflectivity measurements.

upper electrode were electrically connected together to allow a voltage to be applied between the upper and lower plate (Fig. 2). The cell was then filled with E7 and inspection under a reflecting microscope showed that a reasonably good monodomain was visible in the regions below the transparent slits in the grating.

The cell was mounted in a THz time-domain spectroscopy set-up [12] adapted to allow measurements in reflection [13], using a THz source with a peak field strength of $1\,\mathrm{kVcm}^{-1}$ over a beam spot size of $\sim 4\,\mathrm{mm}^2$. To prevent distortions in the measurements due to the absorption of radiation by water vapour in the atmosphere the experiment was contained in a nitrogen-rich atmosphere at room temperature. The cell was orientated to allow the THz pulse to be incident on the grating face of the cell at a small ($\sim 10^\circ$) angle of incidence and polarised perpendicular to the slits. The reflected pulse was recorded in the time-domain with the cell shorted and the liquid crystal homogeneously aligned. A series of voltages, up to a maximum of 20 V peak-to-peak with a frequency of 10 kHz, were applied to the cell and for each voltage the director was allowed to reach equilibrium ($\sim$20 seconds) before the reflected pulse profile was measured. The beam profiles for each voltage were then converted into intensity versus frequency using the Fourier transforms of the time domain measurements. These results were then normalised to the intensity spectrum of the incident THz pulse in free-space, measured by replacing the sample with a silver mirror.

RESULTS AND DISCUSSION

The measured intensity versus frequency profiles for 0 and 20 V are shown in Figure 3. The data exhibits a series of dips in the reflected

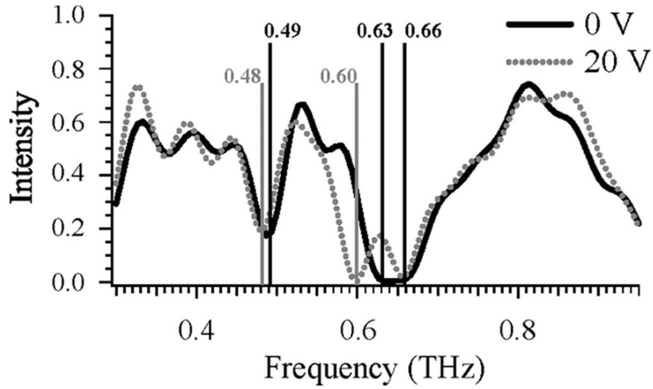

FIGURE 3 Measured reflected intensity (arbitrary units) versus frequency for a THz pulse polarised perpendicular to the slits of the sample shown in Figure 2 with 0 V and 20 V peak-to-peak voltages applied across the liquid crystal at a frequency of 10 kHz.

intensity of the THz pulse. There is a modest difference in the measured response at 0 V and 20 V over this frequency range, particularly note the shifts in the frequency of the sharpest resonances in the system. At 0 V a sharp minimum is seen in the reflected intensity at 0.49 THz and a second, broader minimum with <1% reflected intensity occurs at around 0.64 THz. From finite element modelling of the system [14] (not shown), this second minimum is thought likely to be due to the overlap of two separate minima located at 0.63 THz and 0.66 THz. This can be confirmed when this reflected intensity profile is compared to the one obtained with 20 V applied across the sample. In this case the position of the 0.49 THz minimum is seen to shift down in position by 10 GHz and the 0.63 THz resonance by 30 GHz. Despite the relatively small shift in position of this minimum, the resulting measurements show that even with this non-optimised device, on the application of a voltage the reflected intensity at 0.60 THz decreases from 30% to almost zero. Interestingly, the 0.66 THz resonance seen at 0 V does not exhibit any change in position on application of the voltage. This suggests that the resonance is therefore due to the fixed pitch of the grating used in the cell rather than the refractive index of the core.

Although clear minima were observed in this THz study, the resonances seen are generally shallower and broader than those seen in the original microwave and optical resonant absorption studies. This is likely to be due to several factors. Firstly, the structure used here was not optimised. Previous work has shown that the sharpest resonances are produced when the slits in the metallic grating are much narrower than the wavelength of the incident radiation. Moreover, the thickness of the dielectric core is critical in determining the absorption resonances: it is likely that the thickness of this cell is allowing Fabry-Perot modes to be generated across the core rather than solely along it. Furthermore, the metallic grating profile used on the incident substrate is likely to create problems with the alignment of the liquid crystal within the cell. As the striped grating is used as an electrode on one side of the cell the regions where the aluminium has been removed prevents a field from being applied across the sections of the liquid crystal below the gaps. This non-uniform index along the core is likely to have resulted in the additional dips in reflection alongside the main minima (due to the well aligned regions) which have been highlighted. Images

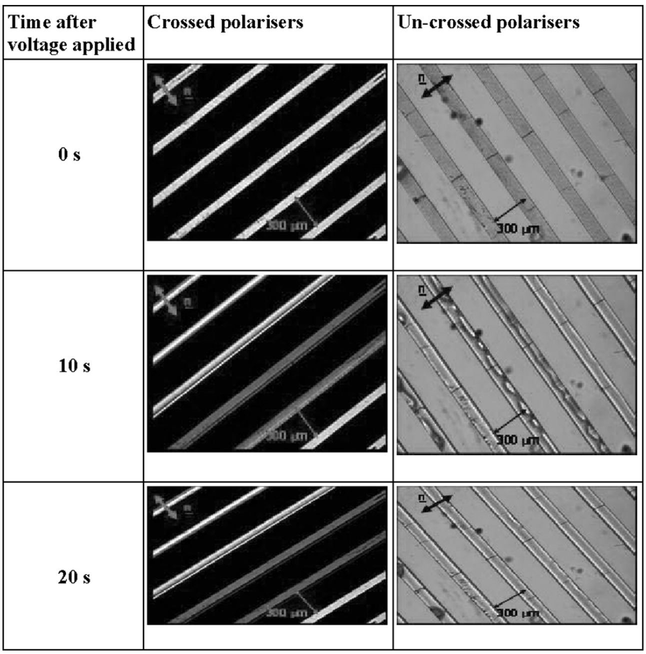

FIGURE 4 Microscope images of a grating cell under crossed and un-crossed polarisers at various time intervals after the application of 20 V peak-to-peak (10 kHz signal). The thicker stripes in each picture are the aluminium grating and the thinner ones are the regions of liquid crystal visible under the grating gaps.

collected from the structure during the switching process when observed in reflection under a microscope are shown in Figure 4. It is clear that the realignment of the liquid crystal underneath the metal stripes has only a small, lateral influence on the liquid crystal in the gaps which creates a non-uniform refractive index along the core. This also means that the switching time for the cell is extremely slow ($\sim$20 s).

Finally, the liquid crystal used in this study (E7) is not optimised for use in this frequency range and the birefringence in the THz range ($\Delta n = 0.152$) [7] is somewhat lower than that at optical frequencies ($\Delta n = 0.217$) [15]. Crucially, the absorption of the liquid crystal is also higher at THz, as is the absorption in the glass coverslip used as the incident substrate. It is this absorption that limits the frequency range explored here and it is believed that to extend this range above 1 THz a more transmissive material such as quartz is required as the incident substrate.

CONCLUSIONS

The use of a clad liquid crystal layer confined between a metal grating and a metal plate as a method for controlling the reflection of THz radiation has been demonstrated. Through applying a voltage across the 100 μm liquid crystal layer the refractive index of the core has been modified, causing a shift in the position of resonant absorptions within the structure by up to 30 GHz. It is believed that this frequency shift will be improved in future devices by using a sample with a thinner core and narrower metal slits, filled with a high-birefringence liquid crystal.

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