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Metal slits and liquid crystals at microwave frequencies

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While the use of liquid crystals (LCs) over the visible region is ubiquitous in flat-screen displays, there has been little by the way of applications at other wavelengths. Specifically, notwithstanding the continuing permittivity anisotropy to be found at longer wavelengths, there has been virtually no development in the microwave domain. This is largely due to the fact that scaling up the micrometer-thick LC layers used for visible radiation to millimetre dimensions is seen as impractical. In this study, it is shown how, using thin slits in metal structures, a completely new generation of LC devices for use at microwaves may be realized. Such structures include slatted metal Fabry–Perot resonators, beam-steering devices, thin flexible voltage tunable filters and even cascade structures with strongly enhanced and reshaped microwave fields.

Keywords: liquid crystals; microwaves; metal slits; tunable structures

1. Introduction

Mobile telephones, laptops, colour televisions and a wide variety of other domestic and commercial products routinely use liquid crystal displays (LCDs) as the visual information modality of choice. Indeed, it would appear that there have been more LCDs made than there are people alive in the world today and it is a ubiquitous technology. Yet its use beyond the visible domain has been very limited. Why this may be is perhaps best illustrated by first examining a standard LCD structure. This is shown schematically in figure 1.

A LC layer at most tens of micrometres thick, which, in the visible domain, is many wavelengths, is aligned by appropriate surface treatment between two glass plates which are coated on their inner surfaces with transparent conducting layers (indium tin oxide). The light is generally incident at close to normal and has its polarization state influenced by the LC such that when a control voltage is applied across the layer, the light may be switched as a result of the changing director profile, and hence optical anisotropy, sensed by the light. Scaling this up to the microwave domain would make the LC layer several millimetres, if not centimetres, thick and would make surface and voltage alignment impossible.

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One contribution of 18 to a Discussion Meeting Issue 'New directions in liquid crystals'.

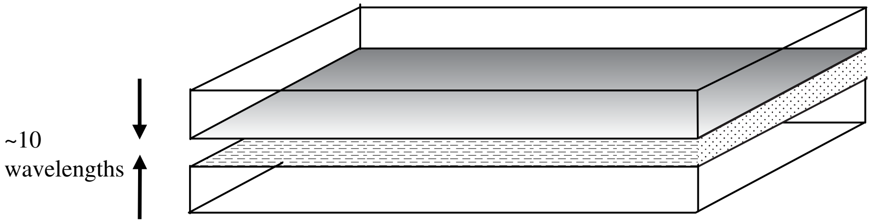

Figure 1. Schematic of simple liquid crystal cell.

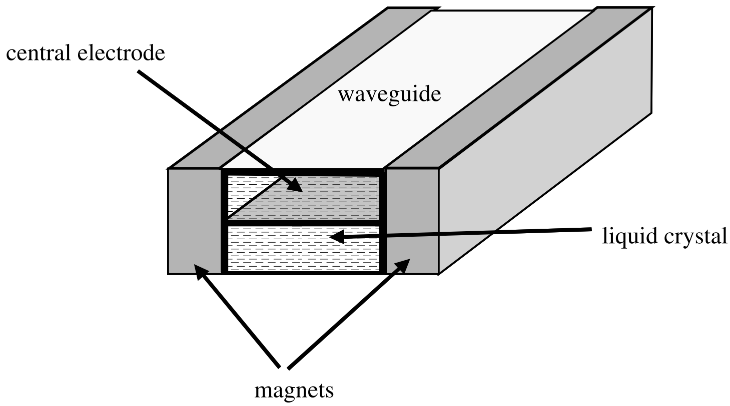

Figure 2. Liquid crystal phase shifter for 30 GHz (see Lim *et al.* 1993).

Thus, this type of naive LC geometry for microwaves is simply not practicable. However, a somewhat equivalent bulk transmission-type device has actually been fabricated by Lim *et al.* (1992, 1993) who included bulk LC inside a waveguide and thereby developed a microwave phase shifter. They incorporated the birefringent LC in a rectangular waveguide in one arm of a 30 GHz interferometer, with the microwave phase shift produced by the LC being compensated for by a 360° mechanical phase shifter in the other arm. A magnetic field of 5 kG imposed upon the LC by a permanent magnet gave a well-aligned monodomain. The director alignment is set parallel to the *E*-vector of the millimetre waves. A central plane electrode, parallel to the sides of the waveguide, as shown in figure 2, allows the application of a modulating electric field to the LC material.

Above a threshold voltage of 60 V, there was an increase in phase shift with increasing voltage that saturated at *ca* 200 V. The response time of the LC alignment to the electric field was of the order of 0.1 s, with a relaxation time under the magnetic field of *ca* 2 s. Guerin *et al.* (1997) also undertook studies of millimetre-wave phase shifters using LC within waveguides. They used microstrip lines with the LC acting as the voltage-controlled phase shifter. Of particular interest is the use of only 50 μm thick aligned LC layers. This is possibly the thinnest LCD constructed for microwave use. This device may also be broadband which gives it substantial application potentials. Tanaka *et al.* (2000) explored the transmission properties of a grating-patterned electrode structure LC cell. The transmittance of the LC cell was found to be 70–80% for polarization parallel to the grating vector and 7–8% for polarization

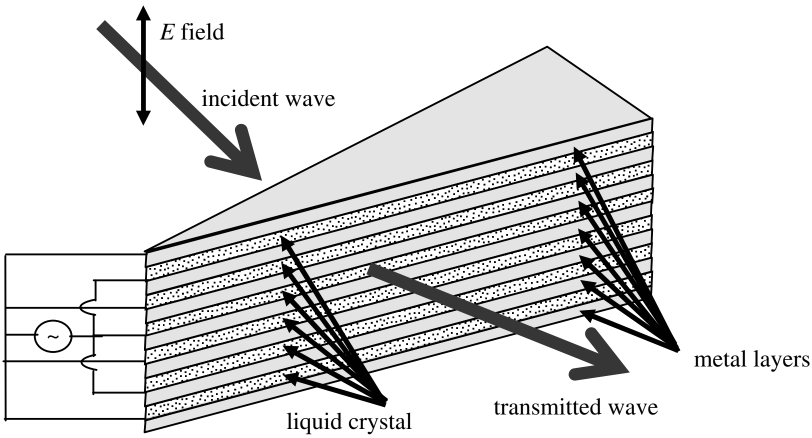

Figure 3. Liquid crystal prism for microwaves (see Tanaka & Sato 2002*a*).

perpendicular to the grating vector. An applied electric field changes the orientation of the LC director which has an effect on the transmissive properties even though the field is inhomogeneous and the director profile non-uniform owing to the grating electrode structure.

Fujikake *et al.* (2001) introduced the use of a fine polymer network to stabilize the director within thick LC cells by use of a photopolymerization-induced phase separation technique. This was applied in a phase shifting structure with a 100 μm thick LC layer, yielding a device with similar phase shifts to previous structures, but with a faster relaxation time due to the elastic constraints of the polymer network.

Tanaka & Sato (2002*a*) appear to be the first to have introduced a stacked structure of interleaved metal and aligned LC. Their first device consisting of a wedge-shaped stack of metal substrates and nematic LC layers, illustrated in figure 3, constituted a microwave prism. It is comprised of 300 μm thick layers of metal with 300 μm thick layers of aligned LC between. To facilitate the LC alignment, the metal substrates were coated with a thin layer of polyvinyl alcohol that was unidirectionally rubbed. By applying control voltages, the permittivity sensed by the microwaves is changed as the director reorients, thereby steering the microwave beam. Note that the microwaves are polarized with their *E* field perpendicular to the metal plates. This allows the microwaves to couple into transverse magnetic modes in the gaps between the metal plates. The orthogonal polarization will not be allowed through the structure owing to the boundary conditions imposed by the metal plates. Furthermore, owing to the substantial amount of metal (50% by area) the transmission is not more than 50%.

The same team of researchers, Tanaka & Sato (2002*b*), also devised a LC cylindrical lens based on the same principles using instead of triangles, a set of planoconvex metal plates as electrode substrates. For this device at 0 V, the director is aligned parallel to the substrate (homogeneous) with a change in focal length occurring when a voltage is applied, which causes the director to align along the direction of the applied field, changing the effective refractive index sensed by the microwaves. A focal length of 78 mm with no voltage applied changed to *ca* 62 mm on application of 10 V.

In addition to the rather obvious polarization limitations, which one might anticipate from optical devices, there are two other limiting factors of the devices discussed so far: they often have rather slow response times and high insertion losses. These issues were in part addressed by Kuki *et al.* (2002) in the construction of a variable delay line. In particular, the use of a dual-frequency LC allows the director to be both driven-on and driven-off, the response being dictated by the frequency of the applied field. The director aligns parallel to the field for frequencies below a few kilohertz, whereas for frequencies in the region of tens of kilohertz, the director aligns perpendicular to the applied field.

At about the same time as these developments in the use of LCs at microwave frequencies were occurring, new research into the transmissive properties of structured metal layers in the visible domain was opening up fresh thinking about the use of structured metals for any electromagnetic waves.

Ebbesen *et al.* (1998) had recorded remarkably enhanced transmission of light through sub-wavelength holes in silver films. This caused an explosion of interest, both theoretical (Martin-Moreno *et al.* 2001) and experimental in the general phenomenon of resonance transmission through periodically modulated metal structures. Thus, even though Ebbesen *et al.* (1998) had used circular holes in metal films, researchers started to pay attention to transmission through any periodic metal structure, including that of narrow slits. Importantly, as we shall see, slit metal structures support (as noted by Porto *et al.* 1999) a family of standing wave states through the metal film. For slits much narrower than the radiation wavelength, these are only supported for radiation with its electric vector normal to the surface of the metal (as illustrated by Tanaka & Sato 2002*a*,*b*).

Unlike the Ebbesen *et al.* (1998) studies in the optical domain, which require nanofabrication procedures, it is rather straightforward to construct sub-wavelength slit structures and to test their electromagnetic response at microwave frequencies. Possibly and even more importantly, the electromagnetic absorbance by the metal due to its finite conductivity is also then expected to have less effect. Early work (Went *et al.* 2000) exploring sub-wavelength slat structures, in which the periodicity was such that no diffraction occurred for the wavelengths examined (zero-order gratings), showed the expected 'filled' Fabry–Perot behaviour. For microwaves incident normally with the polarization orthogonal to the metal slats, there were a series of resonant transmission peaks each corresponding to a wavelength that was approximately an integer fraction of twice the slat length (length of the 'filled' Fabry–Perot). Further work (Hibbins *et al.* 2001) took this idea to two dimensions using a 'wall' of metallic bricks, which thus have slits in two orthogonal directions. This gave resonance transmission of microwaves for any incident polarization. In all these studies, slits were used, which although less than half a wavelength wide were generally beyond 250 μm. This is certainly far from that used in LCD devices where a typical cell thickness is of the order of 10 μm; required partially to allow good alignment of the LC director. Thus, it is of interest to examine the response of metal slat structures with rather thinner gaps, for filling such gaps with well-aligned LCs should not be too difficult.

2. Transverse magnetic modes in thin waveguide

The essential problem concerns that of the waveguide modes associated with a very thin parallel plate capacitor. For microwaves, this is normally solved by considering the metals to be perfect conductors. However, this is actually rather seriously in error for the thickness of gaps considered. This is a well-explored waveguide problem (Yang *et al.* 1991) and the dispersion equation for a slit of width w containing a medium of relative permittivity, ϵ_1, trapped symmetrically within a metal of relative permittivity, ϵ_2, is

$$\tan\left(\frac{\alpha_1 w}{2}\right) = -\frac{\epsilon_1 \alpha_2}{\epsilon_2 \alpha_1}, \tag{2.1}$$

where $\alpha_i^2 = k^2 - \epsilon_i k_0^2$, with k_0 being the free-space wavevector. For this case, the slit width w is much less than the wavelength, where equation (2.1) may be approximated to

$$\frac{\alpha_1 w}{2} \approx -\frac{\epsilon_1 \alpha_2}{\epsilon_2 \alpha_1}. \tag{2.2}$$

For microwave frequencies, the metal permittivity is approximated by $\epsilon_2 = i\sigma_0/\epsilon_0\omega = \epsilon_r - i\epsilon_i$, where σ_0 is the conductivity (typically $\epsilon_r \sim 10^3$ and $\epsilon_i \sim 10^7$). Then, ignoring ϵ_r and taking $\alpha_1 = 1$ (air), $\alpha_2^2 = k^2 - \epsilon_2 k_0^2 \approx k^2 + i\epsilon_i k_0^2 \approx i\epsilon_i k_0^2$ and equation (2.2) reduces to

$$\alpha_1^2 w \approx \frac{2\sqrt{i}|\epsilon_i|^{1/2} k_0}{-i|\epsilon_i|} \approx \frac{2k_0}{|\epsilon_i|^{1/2}} \mathrm{e}^{i3\pi/4}. \tag{2.3}$$

In turn, since $\alpha_1^2 = k^2 - k_0^2$, this leads to

$$k^2 \approx k_0^2 + \frac{2k_0}{|\epsilon_i|^{1/2} w} \mathrm{e}^{i3\pi/4}. \tag{2.4}$$

This shows that the lowest order (almost plane wave) transverse magnetic mode, which exists between two parallel metal plates spaced a small distance apart, has its wavevector modified from k_0 by the finite conductivity of the metal. For thin slits, which are appropriate for aligning LCs, w may be 10 μm. In this case, this correction term is of the order of 10%, tending of course to dominate for impossibly thin slits. However, this shift in resonant frequency does not concern us too much. Of greater significance is the broadening of the resonant mode brought about by the resistivity. Expanding equation (2.4) to first order gives

$$k \approx k_0 - \frac{k_0 \lambda}{|\epsilon_i|^{1/2} 2\pi w \sqrt{2}} (1 - i). \tag{2.5}$$

From this expression, it is apparent that the frequency shift of the resonant mode is the same as the mode broadening. This will have a very significant effect as the slit is reduced in thickness below *ca* 50 μm. This suggests that trying to develop microwave devices with metals and LC layers less than such a thickness is not particularly wise.

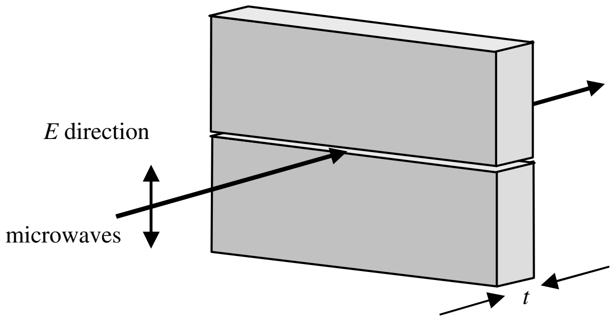

Figure 4. Geometry to be explored for resonant transmission of a single variable width slit in a metal plate. The E field of the incident microwaves is orthogonal to the slit and the microwaves are incident normally on the metal plate.

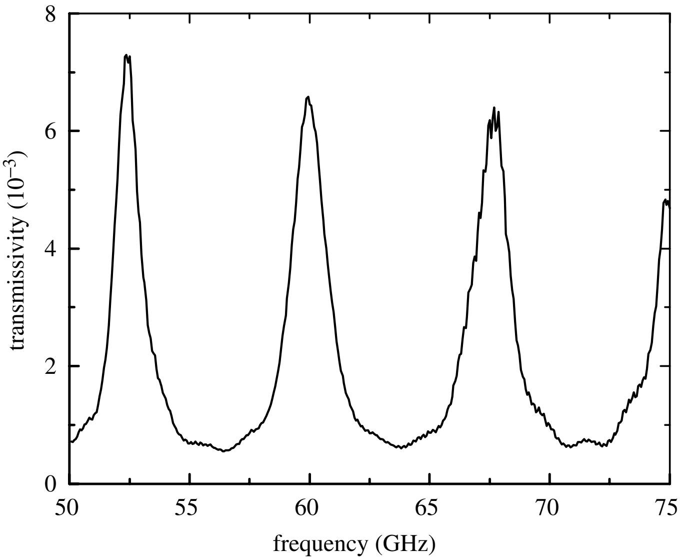

Figure 5. Typical microwave transmission for a slit width of 250 μm.

3. Results

(a) Single slits

(i) *Without liquid crystal*

The simplest slit geometry is shown in figure 4. The microwave transmissivity of such a structure, as the frequency of the source is varied, is presented in figure 5. This shows a series of resonant peaks with frequencies closely specified by the simple Fabry–Perot expression

$$f = \frac{cN}{2tn}, \tag{3.1}$$

where N is an integer, n the refractive index of the dielectric between the metal plates and c the velocity of light.

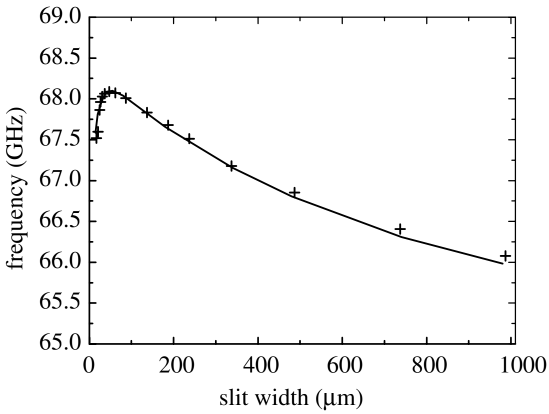

Figure 6. Resonant frequencies (corrected by -0.035 ± 0.008 GHz for beam width effects) for one Fabry–Perot mode as a function of slit width. Data (crosses) are compared with finite element modelling using ANSOFT's HFSS software with a conductivity of 1.7×10^7 S m^{-1} (solid line).

The results of a detailed study of the effect of changing slit width on these resonant modes (Suckling *et al.* 2004) confirm that there is indeed a strong influence of the finite conductance of the metal for gap thicknesses below *ca* 80 μm, as shown in figure 6. The microwave fields within the slit are almost plane-wave-like in character, with resonant frequencies closely matching the predictions of equation (3.1), which for figure 6 would correspond to 68.7 GHz. The results show that the boundary conditions on the microwave fields at the entrance and the exit apertures also influence the resonant frequencies. For wide slits, there is a significant reduction in resonant frequency due to the distortion of the phase fronts at both the entrance and the exit faces. This does not concern us greatly. More significant is the confirmation of the theory mentioned earlier for thin slits. This shows that reducing the slit width below *ca* 50 μm reduces the resonant frequency and correspondingly broadens the resonance, signifying increased absorption and higher insertion loss. Confirmation of this effect is obtained by comparison to the predictions of a finite element modelling code (HFSS, Ansoft Corporation) where there is full agreement with the predictions.

(ii) *With liquid crystals*

Two aluminium plates are placed together with a 75.0 μm slit (see figure 7), established by insulating Mylar spacers at each short end (Yang & Sambles 2001). The rather narrow gap between the two plates is filled with a small amount (less than 0.1 cm^3) of nematic LC. In order to give alignment of the LC, two inner surfaces of the aluminium plates forming the walls of slit cavity are first polished to mirror quality and then spin coated with a polyimide (AL 1254, JSR Corporation). They are subsequently baked and unidirectionally rubbed along a direction parallel to the short edge of the plates leading to good homogeneous (planar) alignment. In addition, the polyimide layers are barriers to ions entering the thin nematic layer when an electric field is applied. Once assembled with the Mylar spacers separating the two plates, the structure is

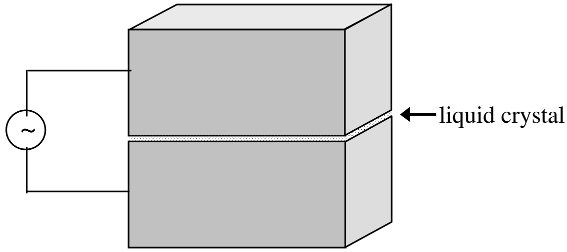

Figure 7. Schematic of single slit filled with liquid crystal to give voltage-tuned microwave transmission.

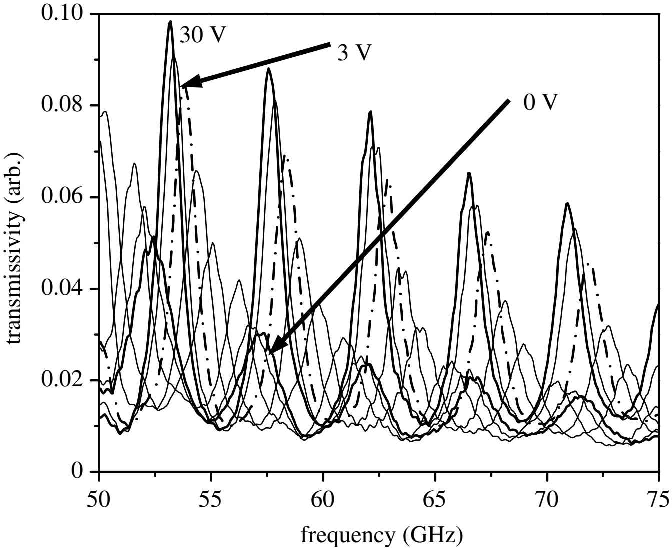

Figure 8. Microwave transmissivity of a single slit filled with aligned nematic liquid crystal between two metal plates.

capillary filled with nematic LC (E7, Merck-BDH) and the metal plates are connected to an AC source (10 kHz) to allow application of voltage across the LC. This single metallic slit sample is then examined for its microwave transmission properties.

From such structures, transmission data were taken as a function of frequency with different voltages (at 10 kHz) applied across the LC. As expected, the resonant transmission peaks move in frequency with voltage. Figure 8 shows typical voltage-dependent transmission spectra over a range of frequencies.

As the voltage (at 10 kHz) is increased from 0.0 to 30.0 V (r.m.s.), the peaks move down in frequency. This corresponds to increased external wavelength fitting into the length of the slit as the voltage increases. With the polarization of the electric field of the incident radiation set to be across the slit, then as the originally homogeneously aligned (parallel to slit walls) LC becomes homeotropically aligned (perpendicular to slit walls) so the index sensed increases. It is also apparent from the figure that one mode step in frequency (*ca* 4 GHz) is encompassed by changing the voltage from 0 to 30 V, although most changes

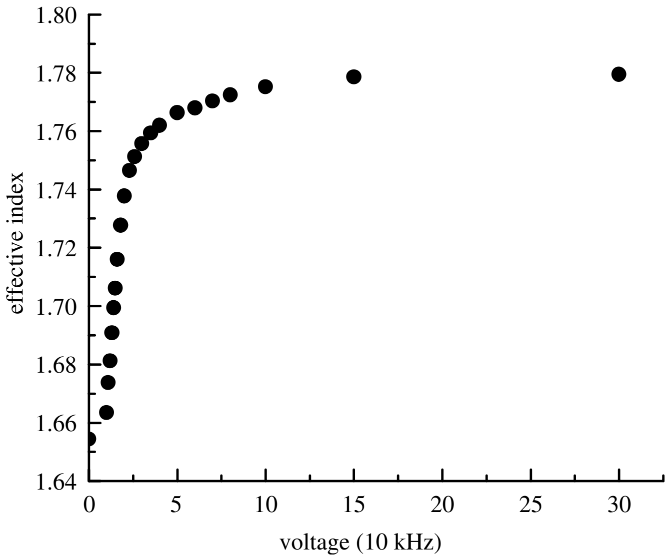

Figure 9. Voltage dependence of the effective refractive index of the liquid crystal deduced from the resonant transmission peaks.

occur over the low-voltage range between 1.0 and 3.0 V. These results show that this LC, E7, may be used as a voltage-controlled wavelength selector in the microwave region.

By use of the simple Fabry–Perot equation (3.1), ignoring end corrections, one may deduce that the mode orders at 0 V are $N=11$–15, with $N=11$ being the lowest frequency mode in figure 8. There appears to be no significant index dispersion of E7 over this frequency region, in agreement with the results of Lim *et al.* (1993). By fitting equation (3.1) to transmissivity peaks, the voltage-dependent refractive index at microwave frequencies is found, as shown in figure 9. From fits to the high- and low-voltage limits, we may deduce an index at 0.0 V of $n=1.654$ and at 30.0 V, $n=1.780$. These are effectively the ordinary and the extraordinary indices of E7, n_o and n_e, in this microwave region, giving an anisotropy of $\Delta n \approx 0.13$ for 50.0–75.0 GHz. This also accords well with the result of Lim *et al.* (1993). This is rather smaller than the optical anisotropy, but it is nevertheless substantial enough to allow the development of useful devices. However, it is clear that single slit structures are unlikely to be of much value as the insertion losses are almost certainly going to be excessive. Thus, one turns to stacks of metal plates and LC layers as demonstrated by Tanaka & Sato (2002*a*,*b*). However, their devices were all non-resonant, not using the Fabry–Perot character allowed by the metal plates.

(*b*) *Multiple slits*

Fabry–Perot-like resonant transmission of microwaves through a stack of metal plates is well known (Went *et al.* 2000). If the stack is constructed such that it is non-diffractive over the wavelength range studied, then it will have a response, which is very similar to that of a single slit, but with much higher transmissivity and much less spreading (single slit diffraction) of the exit

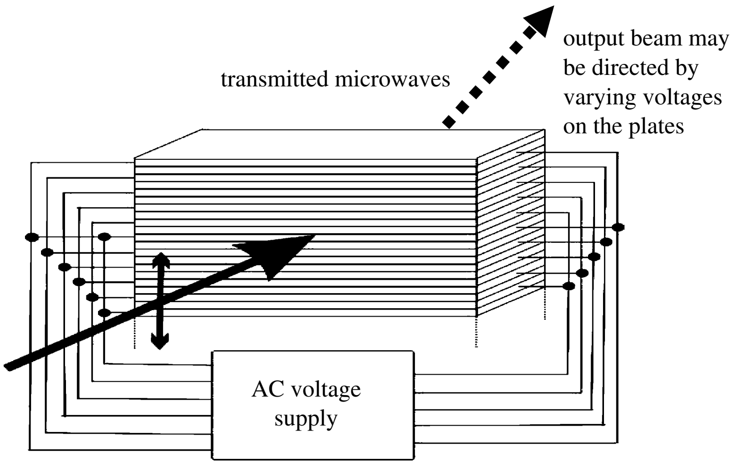

Figure 10. Part of a liquid crystal-filled metal slat structure that comprises a voltage-tuned microwave beam-steering device.

beam. It is thus a relatively straightforward matter to take the single slit filled with LC and build, using multiple slats, a much more strongly transmitting structure. In order to demonstrate the potential, beyond acting as voltage tuneable filters, a LC-filled multiple stack has been constructed with blocks of 10 cells as shown in figure 10. This comprised in total a stack of 71 strips of aluminium with Mylar spacers at each end. Such a structure does more than just providing a selective filter (Yang & Sambles 2004). It is possible to control the phase of microwaves in different cavities. Suppose on one cavity, the voltage applied is such that the cavity is tuned just to the high-frequency side of a resonance and a further cavity is tuned to the low-frequency side of a second resonance. The combined signal from these two will interfere and since they have different phases on exiting the cavity, the maximum combined transmitted beam will no longer exit the sample parallel to the input beam. We have the potential for beam steering. To facilitate high throughput, the 70 gaps in the structure are divided into seven groups of 10 gaps within each group. An AC source (1.0 kHz) is used to apply different voltages to each gap within one group with the gaps having the same relative position within different groups having the same voltage across them. This results in a set of seven identical groups of 10 slats. These 10 slats give a repeat distance of 10.75 mm. As before, each single slit is fabricated with rubbed polyimide aligning a layer of E7 nematic LC and only linearly polarized microwaves are incident with the electric vector lying perpendicular to the slats. There is no transmission for radiation polarized with its E field along the slat direction. The transmission data were taken as a function of frequency with various combinations of voltages across the LC-filled gaps and beam steering was effected of the order of tens of degrees.

While these types of devices may be useful, they are rather bulky and it would be much better if one could devise a way of making much thinner structures. Owing to the recent developments in studies of the electromagnetic response of structured metal surfaces, this can indeed be done.

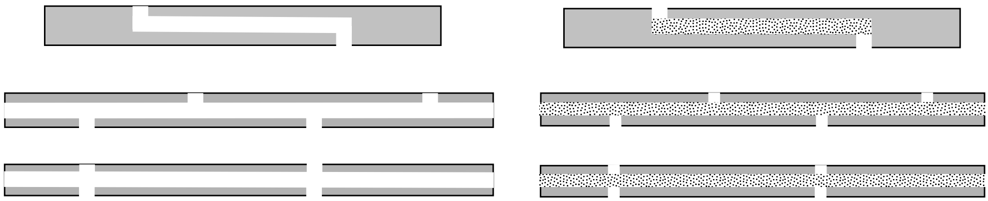

Figure 11. Thin slit structures. The upper left one is equivalent to the single slat while the lower two are multiply connected versions. On the right are structures filled with polymer-dispersed liquid crystals, which may act as voltage-tunable devices.

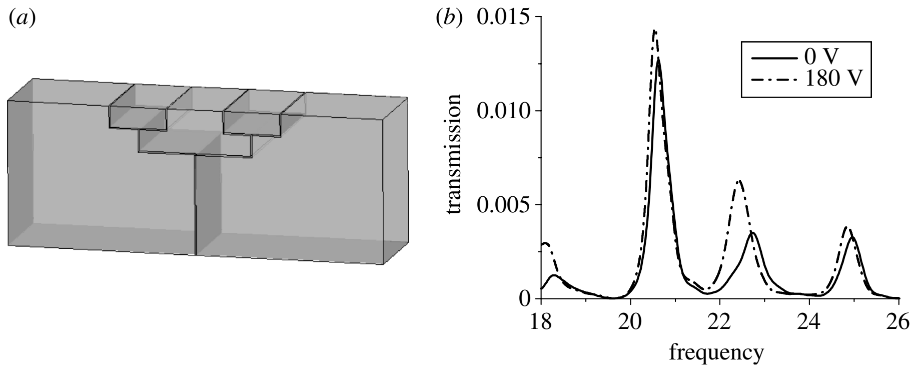

Figure 12. (a) A cascade structure in which the polymer-dispersed liquid crystal (PDLC) fills the longest slit. When voltages of the order of 180 V AC are applied to realign the PDLC the resonant modes with large fields in the long portion of the cascade are moved in frequency. This is shown in (b).

(c) *Thin structures*

It only takes a little thought to grasp that the 'filled' Fabry–Perot slat devices considered earlier lend themselves to a much thinner possibility. This is appreciated when one realizes that the slits do not have to be at right angles to the metal wall and that they do not have to be straight. Consider the simple structures shown in figure 11. All these are essentially slat structures that now, instead of being very thick, can in principle be reduced to a few tens of micrometres. The Fabry–Perot repeat distance is dictated by the length of slit along the structure rather than through it.

These types of structure have been studied in detail (Hibbins *et al.* 2004) for both the resonant absorption and resonant transmission of microwaves. As anticipated, they act in much the same way as the slat structures except that multiply connected structures are available. These thin structures may be readily filled with LC although, to make robust devices, it is perhaps advisable to use polymer-dispersed liquid crystals (PDLCs).

These structures are only the beginning of the investigation into the behaviour of a whole range of devices for controlling microwave radiation. It is a simple step to conceive of multilayer devices with different effective refractive indices in each layer, allowing the structure to resonantly transmit over a range of different frequencies. There is also the potential for use of semiconductors to replace the normal metals. These also give voltage tuning of their dielectric response function at microwave frequencies; but even these rather elegant structures are not the end of the story. There is no reason why with transverse magnetic radiation able to penetrate into thin metal gaps and travel around tight bends, one cannot fabricate even more elaborate cascade structures; such a structure is shown in figure 12. Here, when 180 V is applied across the PDLC in the lower slit, the transmission resonance at *ca* 22.8 GHz shifts significantly. Then, there would appear to be enormous scope for combining LCs with slit metal structures at microwave frequencies.

4. Conclusions

From the above, it should be clear that the use of thin metal slits filled with nematic LCs has the potential for yielding novel types of microwave devices. Of course, LCs still need to be developed which have low absorption loss at microwave frequencies to make low insertion loss devices as selective filters and beam steerers. Those used so far have only been optimized for the visible. Once better LCs are available, with possibly higher dielectric anisotropy at microwave frequencies also, then the incorporation of voltage tunable LCs in other only recently realized very thin microwave structures looks likely to be very interesting. Through the use of PDLCs with thin metal coatings (less than 2 μm will be sufficient to screen the microwaves) flexible large area structures are an obvious possibility. Further, with cascade structures, the possibility of microwave field intensification arises. This may well lead to heating effects, but also has the exciting prospect of nonlinearity.

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Discussion

N. J. Smith (*Sharp Labs of Europe, Oxford, UK*). What do you think would happen if you spatially modulated the LC switching within a cavity?

J. R. Sambles. If I understand your question correctly and one spatially modulates the LC switching within a single cavity through the length of the cavity then I suspect all that happens is mode broadening for that particular cavity, with different regions within the cavity giving different effective microwave indices. This would result in an effective decrease in the Q of the overall structure. However, and perhaps this is what you are really hinting at, if one periodically modulates along, rather than through, a single slit then it may be possible to obtain diffraction and beam-steering effects in the plane of the slits. In principle lensing may be possible (bearing in mind that resonance is still required); clearly this may introduce a further range of device possibilities.

S. J. Cowling (*Department of Chemistry, University of Hull, UK*). What are the limits on birefringence for the microwave device? Could you comment on problems associated with the device relative to the changes?

J. R. Sambles. I imagine the limits to birefringence are of the order of the range available optically. Indeed, since the lower frequency dielectric anisotropy is larger than that found at optical frequencies one might hope for increased birefringence over that found optically, although from our experimental results thus far this does not appear to be the case.

D. Lacey (*Department of Chemistry, University of Hull, UK*). What switching times do you require from the LC material and is the switching speed more important than its birefringence (Δn)?

J. R. Sambles. Up until now we have not concerned ourselves too much with switching times. Clearly, for an ordinary nematic LC, we are limited to switch-off times of the order of tens of milliseconds. We are exploring the possible use of dual frequency materials to allow drive-on as well as drive-off. Unfortunately such dual-frequency materials have reduced dielectric anisotropy and consequentially require much larger fields to give the same sort of switching. In addition we have been exploring the use of polymer networks to confine the LC material in the rather large (approx. 100 μm) cell gap and this polymeric structure tends to further slow the switching process. Birefringence is actually quite large, although, as indicated in my earlier answer, somewhat smaller than that found at optical wavelengths, so this is not really a problem.

P. Palffy-Muhoray (*Liquid Crystal Institute, Kent State University, USA*). Through what angles were you able to steer your microwave beam?

J. R. Sambles. By suitable combination of voltages in the slat structure we were easily able to steer the beam by more than 10° to either side of normal, sufficient for forward looking radar for example. Increasing the voltage applied to the various slats gave higher angles but there is associated with this a corresponding loss in signal strength as one tunes the resonances in different slats to be further off the wings of the chosen resonance.

H. F. Gleeson (*School of Physics and Astronomy, University of Manchester, UK*). What is the main contribution to the microwave absorption in the molecular structure/interactions of the LCs?

J. R. Sambles. It would be nice to be able to quote you some results for microwave absorption spectroscopy on the materials we have been working with so that I could be absolutely clear about this but I am unaware of results from any detailed experiments of that character on these liquid crystals. Of course at these microwave frequencies the most likely contributions to absorption will arise from rotational transitions. One might also expect contributions from any dipoles that have Debye relaxation frequencies in this region of the spectrum, and these could be problematic as they may cause serious heating of the sample.