AFRL-AFOSR-UK-TR-2011-0044

CdTe-based Light-Controllable Frequency-Selective Photonic Crystal Switch for Millimeter Waves

Vladimir B Yurchenko

National University of Ireland Maynooth
Experimental Physics Department
Main Street
Maynooth, Ireland 00000

EOARD GRANT 10-3086

September 2011

Final Report for 25 August 2010 to 25 August 2011

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
23-09-2011	Final Report	25 August 2010 – 25 August 2011

4. TITLE AND SUBTITLE

CdTe-based Light-Controllable Frequency-Selective Photonic Crystal Switch for Millimeter Waves

5a. CONTRACT NUMBER
FA8655-10-1-3086

5b. GRANT NUMBER
Grant 10-3086

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Dr. Vladimir B Yurchenko

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National University of Ireland Maynooth
Experimental Physics Department
Main Street
Maynooth, Ireland 00000

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR/RSW (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-UK-TR-2011-0044

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Frequency-selective mm-wave photonic-crystal (PC) beam switches of increased sensitivity for rapid turning off and on quasi-optical beams in response to light pulses as control signals have been designed, manufactured and experimentally tested.
Light-controllable PC-enhanced devices using semiconductor wafers (semi-insulating GaAs and Si layers or CdTe-coated quartz plates) with special surface patterning will provide additional functionality for mm-wave beam processing, with sensitivity improved, according to simulations, by 2 to 4 orders of magnitude as compared to a single-wafer device.
Experimental testing of light sensitivity of different kinds of PC structures when using a flash lamp as a light source proved a possibility of making mm-wave PC devices capable of switching quasi-optical beams with available inexpensive light sources.
Quartz-air PCs with a Si wafer insertion have shown extreme sensitivity due to slow electron-hole recombination (tR~50µs) and thick photoconductive layer in silicon (*L*=0.3mm) that allows one to completely turn off the transmission peak at *f* = 92.5 GHz by the light pulse of intensity *I* ~ 0.4 W/cm2 (the PC transmission peak is reduced by 30 dB in response to the light whereas a single Si wafer transmission drops only by 4 dB).
Similar kinds of PCs using CdTe-coated quartz wafer insertions, likewise GaAs wafers, are less sensitive to the light due to small recombination length (*L* ~ 3 µm) in CdTe and GaAs. Yet, a flash lamp illumination proved to be sufficient for observing a reduction of transmission peak of PC.
Use of CdTe-coated quartz wafers and, even more so, plastic PCs and CdTe films on flexible substrates, promises essential advantages over conventional design solutions that makes it worthwhile to extend the developments in this direction. Use of surface patterning should also increase the light sensitivity of devices that requires further improvements in the technology of CdTe films with various kinds of metallic patterns.
Thus, due to high quality of PC structures at mm-waves and special methods of surface impedance optimization, the PC-based devices can be made to operate at a reduced light intensity avoiding the use of powerful lasers that makes them more suitable for practical applications.

15. SUBJECT TERMS

EOARD, Millimeterwave technology, photonic materials

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			A. GAVRIELIDES
UNCLAS	UNCLAS	UNCLAS	SAR	32	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616205

European Office of Aerospace Research and Development

Grant Award

FA8655-10-1-3086

Final Report

CdTe-based Light-Controllable Frequency-Selective Photonic Crystal Switch for Millimeter Waves

V. B. Yurchenko

NUI Maynooth, Ireland

22 September, 2011

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Summary

The goal of this work is the design, manufacturing and testing of extra-sensitive light-controllable millimeter-wave (mm-wave) beam switches based on photo-sensitive CdTe layers used as a mini-resonator inside of a Bragg structure of quartz wafers that operates as a mm-wave photonic crystal (PC) for enhancing photo-response of the entire system.

Quasi-optical switches belong to a broad class of semiconductor-based light-sensitive structures that can rapidly turn on and off the transmission of mm-wave beams in response to the light pulse as a control signal that operates the device. Enhancement of the device occurs due to the possibility of increasing the mm-wave amplitude at a semiconductor layer in a PC that results in strengthening the coupling between the wave and the device. The enhancement is, generally, frequency-selective and, in some cases, could be of a few orders of magnitude.

Other methods for further increasing the device sensitivity are also possible. They could use, e.g., modification of surface impedance of semiconductor wafers (where, actually, photoconductivity is induced) by utilizing special patterning of semiconductor surfaces. The latter results in altering both the real (active) and imaginary (reactive) parts of surface impedance at mm-waves that affects the mm-wave propagation through the device.

In this work, we show that quartz-air PCs with a Si wafer insertion have extreme light sensitivity that allows one to completely turn off the PC transmission peak at $f = 92.5$ GHz by the light pulse of peak intensity $I \sim 0.4$ W/cm^2 (the PC transmission peak is reduced by 30 dB in response to the light whereas a single Si wafer transmission drops only by 4 dB).

Similar kinds of PCs using CdTe-coated quartz or GaAs wafers are less sensitive to the light due to small recombination length in CdTe and GaAs. Yet, a flash lamp illumination proved to be sufficient for observing a reduction of transmission peak of PC.

Thus, due to high quality of PC structures at mm waves, devices considered in this work can be operated at a significantly reduced light intensity, e.g., when using stroboscopic flash lamps rather than powerful laser sources, that makes these devices more suitable for practical applications.

Once the use of CdTe-coated quartz wafers and, even more so, plastic PCs and CdTe films on flexible substrates promises essential advantages over available design solutions, it makes worthwhile to extend the developments in this direction.

Keywords: millimeter wave, quasi-optical beam, Bragg structure, photonic crystal, light-controllable device, semiconductor structure, thin film, optoelectronic switch, multiplexer.

3. Introduction

Progress in modern optoelectronics and communication technology requires rapid development of new kinds of devices, particularly, those based on various types of photonic crystals (PCs). PCs can be used as nearly ideal pass-band and stop-band filters, low-loss mirrors, high-quality resonators and modulators, ultra-fast switches and multiplexers for electromagnetic waves ranging in frequency from visible light to millimeter waves [1].

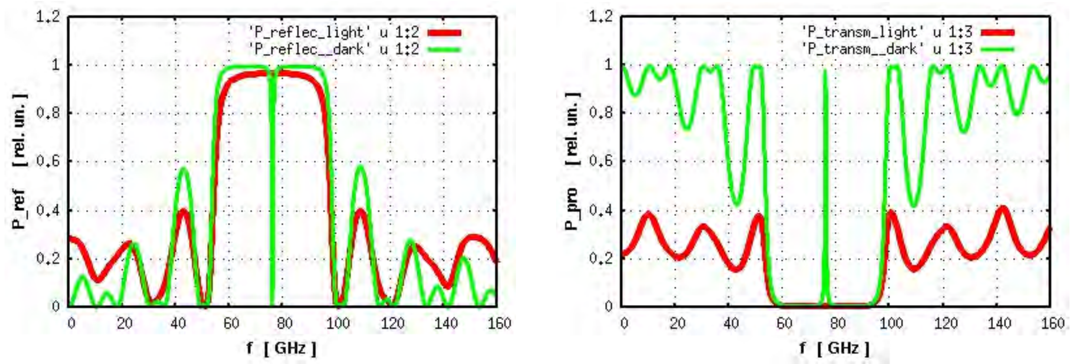
For extra functionality, PCs have to be controllable, i.e., to be able to alter their properties (e.g., operation frequency bands) in response to external signals such as light and electric and magnetic fields [2-6]. In this case, high speed and depth of modulation are essential, which are better achieved when using so called "defected" PCs (PCs with intentionally created defect of periodicity) that allow greater concentration of the mm-wave field in active regions of the PC [5, 6].

The best functionality is provided by optical and electronic control of devices [4-6]. A good example is an ultra-fast quasi-optical switch of extremely powerful microwave radiation, which is capable to switch up to 100 MW of microwave power in 10 ns [7]. An essential drawback of switch [7] is, however, a need for the powerful laser system for the optical control of the device. If a proper PC structure is used for enhancing the light control in a narrow frequency band of millimeter-wave beams, far less powerful light is needed and less expensive components can be utilized.

A possibility of PC enhancement of light-controllable mm-wave switch is illustrated by the results of computer simulations as shown in Fig. 4.1. Fig. 4.1 shows an example of dark- and light-state reflection and transmission spectra (in relative units) computed for the PC of six quartz wafers with CdTe-coated double-wafer insertion which demonstrate a frequency selective switch between the reflective and transmitting states at the resonant frequency $f = 75$ GHz. The switch operates at the resonant frequency only, which is the result of the defect layer insertion in the PC leading to the resonant concentration of mm waves at the CdTe-coated surfaces, which reduce their impedance due to illumination.

Generic idea of a light-controllable defect-layer PC structure of such a kind was implemented recently in the form suited for THz applications [8]. Using a SiO_2-MgO PC structure with a GaAs light-sensitive defect layer, an ultra-fast THz-band opto-electronic switch has been created and successfully tested in the band of $f = 0.3$ - 0.9 THz, with the main operation frequency $f_0 = 0.6$ THz.

In this form, the switch still requires a powerful Ti:sapphire laser as the light source. So, with no other means of increasing the device sensitivity, it remains of relatively conventional functionality as for this kind of devices (because of low quality factor of the given PC at the THz frequencies, Q ~ 36, and rather small aperture being used, D = 4 mm, there is no room here for significant improvements of the particular device).



(a) (b)

Fig. 4.1. (a) Reflection and (b) transmission mm-wave spectra of light-controllable CdTe-based fused-quartz photonic crystals estimated by numerical simulations: a dark-state reflection dip and transmission peak at the frequency f = 75 GHz (light green curves) disappear under illumination (dark red curves)

In the millimeter-wave band (f = 30 – 300 GHz), light-controllable PC devices of similar kind have not been implemented yet. In the meantime, the conditions for their implementation are much better at these frequencies due to availability of high-quality materials, easier manufacturing of structures, lower microwave losses, etc.

A particularly prospective way forward is the use of novel materials. A suitable material is a photoconductive CdTe film deposited on a quartz substrate. When using modern technology [9-11], CdTe films of sufficient quality could be produced that makes manufacturing of CdTe-based light-controllable millimeter-wave PCs feasible.

An additional possibility for further increasing the device sensitivity is the use of special surface metallization and patterning of semiconductor layers. This results in altering both the real (active) and imaginary (reactive) parts of surface impedance at mm waves that can be used for reducing the effective high-frequency surface impedance under illumination in a way similar to methods developed for obtaining negative dielectric permittivity and magnetic permeability of composite metamaterials [12]. In this way, a photosensitive PC structure of double-negative metamaterial can be created that should result in further improvement of quasi-optical mm-wave beam switches.

4. Methods, Assumptions, and Procedures

Light-controllable mm-wave beam switches will be developed on the basis of one-dimensional PC structures made of low-loss quartz wafers. A light-controllable structure is obtained by inserting a semiconductor layer in the PC, thus, making its mm-wave transmission properties light sensitive and frequency selective. The layer increases the amplitude of mm waves on semiconductor surfaces at the resonant frequencies, thus, increasing the light sensitivity of the PC.

Our recent experiments made at the NUI Maynooth with an assembly of four GaAs wafers (Fig. 5.1) supplied us with necessary proofs on technical feasibility of this idea (see below).

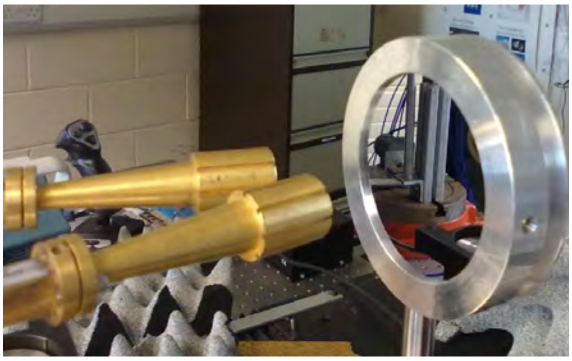


Fig. 5.1. A model GaAs PC assembly used in the feasibility test on development of light-controllable beam-processing devices

Semiconductor layers could be of Si or GaAs wafers of optimal thickness, with or without special surface patterning designed for enhancing effective surface impedance under illumination. The latter can be achieved by using some metallization patterns, e.g., similar to those used in the design of double-negative materials [12].

Another option is the use of thin-film CdTe layers deposited on quartz substrates. Thin-film CdTe layers could be obtained with technology available at the Kharkov National Polytechnical University (Kharkov, Ukraine). This can provide essential benefits in costs, mechanical strength of wafers, kinds of surface patterning, etc.

The main benefit of CdTe is the mechanical strength of substrates as compared to, e.g., GaAs wafers, since the latter could easily be broken at so small thickness (of sub-millimeter range) as needed for mm-wave switches. In the meantime, both the materials are quite comparable in their photoconductive properties, with a possibility of making them either extra-sensitive or, alternatively, fast-operating in response to the light signals.

An example of a PC structure of this kind is shown schematically in Fig. 5.2 (we shall use a self-explanatory notation ‘4q-sqqs-4q’ to describe the composition of such structures). Here, the dielectric plates (shown as blue strips) are the wafers of electric fused quartz of standard thickness t = 0.500 mm (the RF loss tangent is $tan(\delta)$ = 0.0001 at the frequency f =

60 GHz according to the manufacturer's specification), photo-sensitive layers (thin red lines) on the opposite sides of the inner twin-wafer insertion (the insertion operates as a defect of periodicity in a PC) are the CdTe thin films of small thickness *s* of about 3 to 5 micrometers, and the gaps between the plates are the air slots of typical thickness a = 1.000 mm.

When making basic estimates and using GaAs parameters as an example, we can show that, in a high-quality photoconductive wafer under illumination of I~10^{17} quanta/cm^2*s (that corresponds to solar illumination at the Earth surface, i.e., 1 Sun), typical surface impedance would be about $Zs \sim (T/e^2) / IL^2 \sim 1.7*10^7$ Ohm (T is the temperature, e is the electron charge, L is the electron-hole diffusion length). So, in this case, we have $Zs >> Zo$ where Zo = 377 Ohm is the impedance of the free space (photo-conductivity in the surface layer would be $\sigma \sim 0.02$ Sm/m). Therefore, it is only illumination of 10^5 Suns that makes a single wafer sufficiently reflective for mm waves in free space ($Zs < Zo$). In a PC structure, however, light sensitivity increases by the PC quality factor Q where, typically, $Q >> 1$.

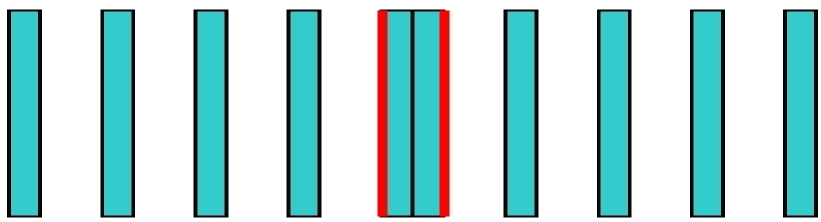


Fig. 5.2. Schematics of a light-controllable PC structure simulated in Fig. 4.1

Estimates made for mm-wave PC structures of commercially available quartz wafers with GaAs defect layer show that PC quality factor may exceed $Q \sim 10^3$ (a defect-layer transparency line-width in this case is about Δf =0.06 GHz at the frequency f_0 = 75 GHz, i.e., the mm-wave lifetime in the PC is $\tau \sim 1/(\pi*\Delta f) \sim 5$ ns). Thus, in the mm-wave band, quartz PC quality factor is by two orders of magnitude greater than the Q-factor achieved at f = 0.6 THz in [8]. This high quality factor, $Q \sim 10^3$, reduces the threshold illumination for switching the device to the level of I ~ 100 Suns only (common for stroboscopic flash lamps) as confirmed by our simulations (this corresponds to σ~2 Sm/m and $Zs \sim 1.7*10^5$ Ohm). Notice, the wafer diameter in mm-wave band should exceed D=70mm (Fig. 5.1) as compared to 4mm aperture size in [8]. The former is compatible with illumination spot of a flash lamp, though may impose extra requirements on re-focused light power density of a laser source.

Thus, basic models and estimates provide us a generic guideline for the design of PC-enhanced light-controllable mm-wave beam switches for possible quasi-optical applications.

5. Theoretical Part: Analysis and Simulations

Theoretical analysis of light-controllable PC structures has been made by applying the transmission matrix approach for simulation of mm-wave propagation through the PC. A dedicated software code has been developed for carrying out computations with account of various imperfections that could be essential in this problem (e.g., RF dielectric losses, oblique wave incidence, beam width and shape effects, etc).

Fig. 6.1 shows the results of computation of transmitted, reflected and absorbed mm-wave power (in decibels) in the dark and under illumination for the CdTe-based twin-wafer

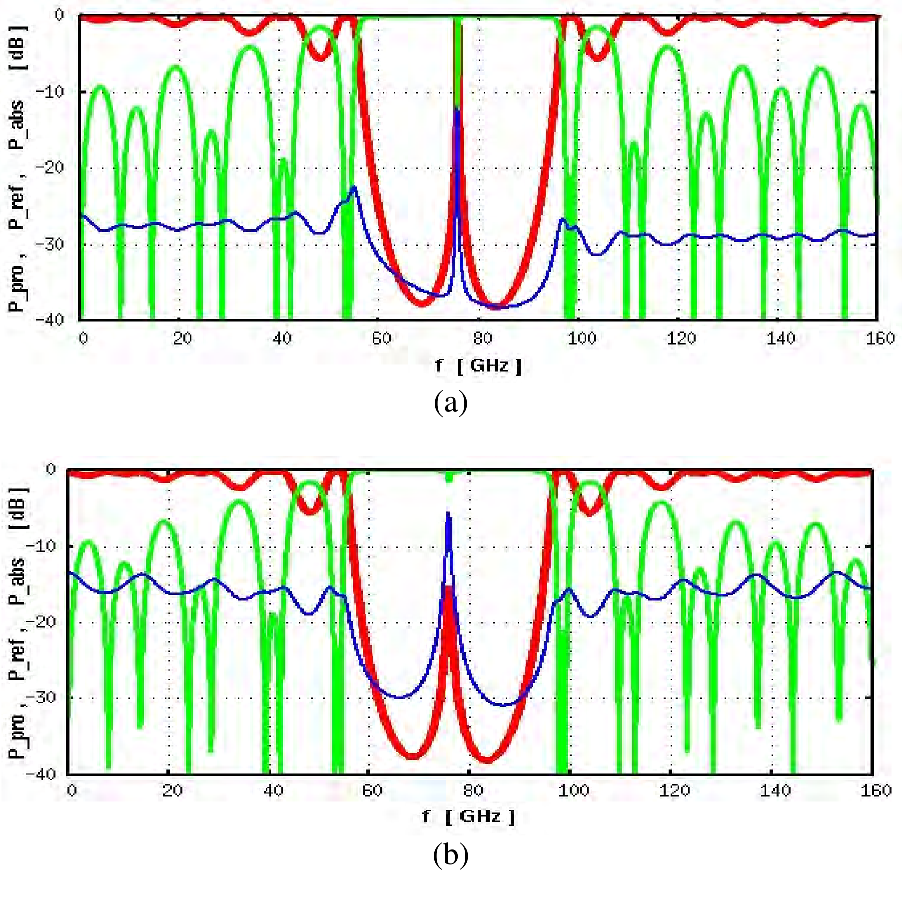


Fig. 6.1. Power of transmitted, reflected and absorbed mm waves (dark red, light green and blue curves, respectively) computed for light-controllable CdTe-based fused-quartz photonic crystals (a) in the dark and (b) under illumination of $I = 0.1$ kW/cm^2 generating CdTe photoconductivity at the level of $\sigma = 20$ Sm/m (dark-state reflection dip and transmission peak at the frequency of $f = 75$ GHz disappear under strong illumination)

defect-layer PC presented in Fig. 5.2. The structure in Fig. 6.1 differs from the one in Fig. 4.1 only by the number of wafers in the basic PC stack (eight in Fig 6.1 instead of six in Fig. 4.1) and the intensity of light, which is assumed to be incident on CdTe films from both sides of the PC structure.

Parameters of PC structures in these simulations are those as explained in Fig. 5.2, with light-sensitive transmission peak at the frequency f = 75 GHz located in the middle of the forbidden frequency band for mm-wave propagation (f = 55–95 GHz). The light intensity is chosen to be so as to provide the effective photoconductivity of CdTe surface layers (of thickness of about the diffusion length of L=3 micrometers) at the level of $\sigma = 10^3$ Sm/m in Fig. 4.1 and σ = 20 Sm/m in Fig. 6.1. This corresponds to the effective surface impedance Zs = 300 Ohm and Zs = 15000 Ohm, respectively, which appears to be sufficient for reliable switching quasi-optical mm-wave beams by the relevant structures in both reflection and transmission modes.

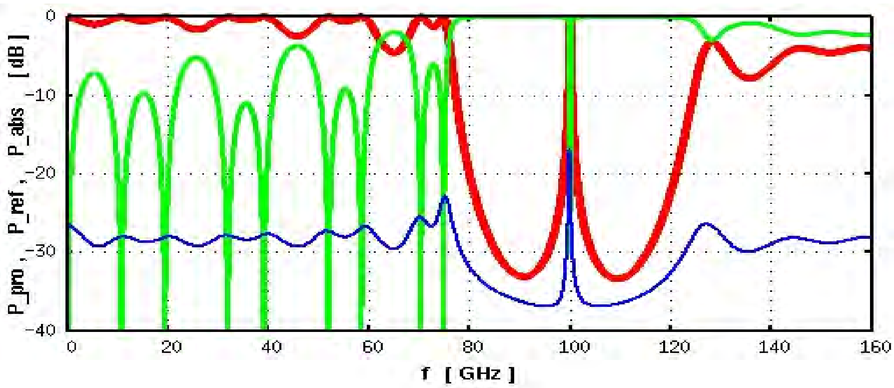
With no enhancement of surface impedance of CdTe layers by any special surface patterning etc, the impedances found above would correspond to the light intensity at the level of about $5*10^4$ and 10^3 Suns, i.e., I = 5 and I = 0.1 kW/cm^2, respectively, which is reasonably accessible in a short-pulse mode of operation. Increasing the number of wafers in a PC, generally, reduces the light intensity needed for the reliable switching. In practice, though, because of mm-wave losses in the dielectric, the optimal number of wafers in the PC would be about six or eight or ten, depending on the reflection or transmission mode of operation and the requirements on the modulation depth of switching.

By applying special surface metallization and patterning that reduces the effective surface impedance in a way similar to manufacturing double-negative metamaterials [12], one can significantly reduce the light intensity needed for the reliable beam switching in a certain frequency range. This, however, should result in a slower operation of the device because of the resonant oscillation processes being involved in the high-frequency effects associated with this kind of surface patterning.

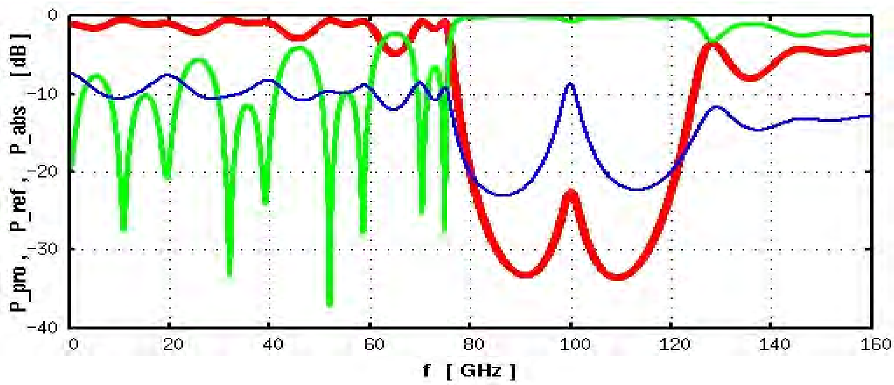
Frequency tuning of transmission peak within the forbidden frequency band for mm wave propagation through the PC at the given thickness of quartz wafers is possible due to certain degree of variation in thickness of both the defect-layer insertion and the air slots between the wafers in the PC.

Fig. 6.2 shows the transmission, reflection, and absorption spectra of CdTe-based defect-layer PC of the same kind as in Fig. 6.1, though having the air slots of smaller thickness a = 0.520 mm and the defect layer that consists of a single quartz wafer coated with relatively thick films of intrinsic CdTe on both surfaces (all quartz wafers are of the same standard thickness t = 0.500 mm and CdTe films are of thickness s = 0.080 mm each, with electron-hole diffusion length being about L = 3 micrometers). In this case, the transparency peak is realized at another frequency of common practical interest, f = 100 GHz, in the middle of forbidden frequency band at f = 75–125 GHz.

Because of greater dielectric constant of CdTe as compared to fused quartz wafers (ε = 8.8 versus ε = 3.8), CdTe films contribute to greater concentration of mm waves at the defect-layer surfaces providing high sensitivity of this structure despite less optimal thickness parameters (Fig. 6.2b corresponds to σ = 100 Sm/m and Zs = 3000 Ohm obtained at the illumination of I = 0.5 kW/cm^2). Dielectric losses of intrinsic CdTe are sufficiently small and do not hamper the structure performance at so small thickness of semiconductor layers.



(a)

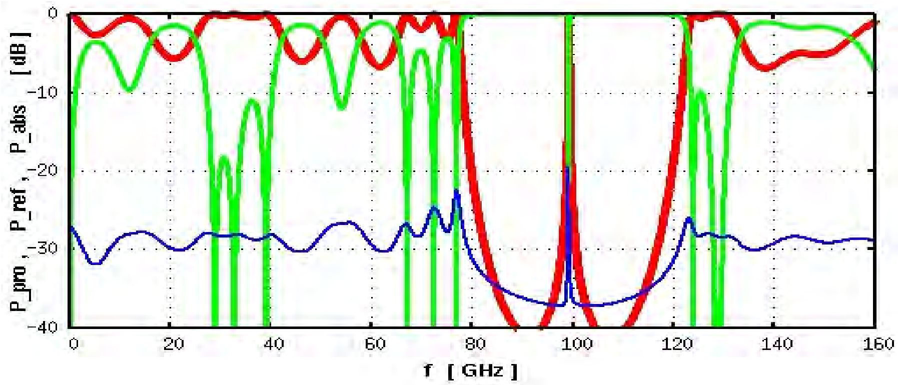


(b)

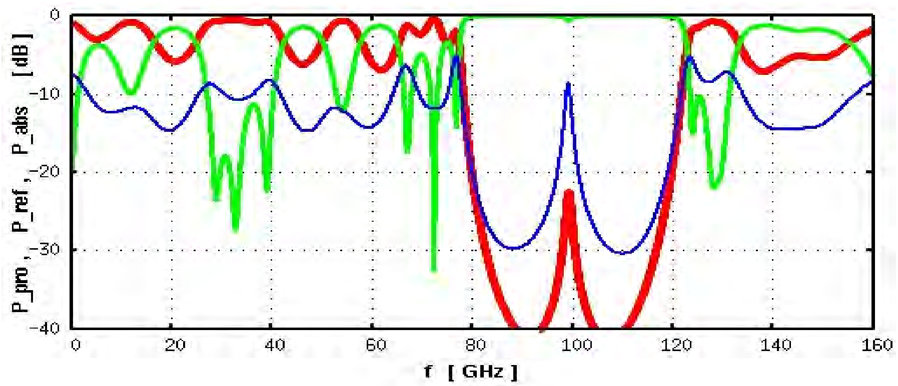
Fig. 6.2. Transmission, reflection and absorption spectra (dark red, light green and blue curves, respectively) computed for CdTe-based fused-quartz PC structure with air slots of reduced thickness a=0.520 mm and relatively thick (s=0.080 mm) CdTe films on a single-wafer defect-layer insertion (a) in the dark and (b) under illumination of I = 0.5 kW/cm^2

A very similar performance at the same transmission peak frequency f = 100 GHz (yet, with a better shaped forbidden band) can also be achieved in this PC structure (Fig. 6.3) when using a twin-wafer semi-insulating (intrinsic) GaAs defect-layer insertion instead of a single CdTe-coated quartz wafer (assuming the same electron-hole diffusion length in both materials, which is often the case for these semiconductors).

Because of even greater dielectric constant of GaAs as compared to CdTe (ε = 13.1 versus ε = 8.8), the forbidden band as deep as –40dB can be obtained in this case, that makes modulation depth of switching accessible at the level of –40dB when using sufficiently powerful light sources for producing the control signals.



(a)



(b)

Fig. 6.3. Transmission, reflection and absorption spectra (dark red, light green and blue curves, respectively) computed for the fused-quartz PC structure with air slots of reduced thickness a = 0.520 mm and semi-insulating GaAs twin-wafer insertion of standard wafer thickness s = 0.640 mm (a) in the dark and (b) under illumination of I = 0.5 kW/cm^2

6. Experimental Part 1: Initial Feasibility Test

An experimental test on feasibility of detection of light sensitivity of mm-wave transmission peaks and refection dips within propagation frequency gaps of certain structures when using a flash lamp as a light source has been carried out (see Fig. 5.1). Two trial structures composed of semi-insulating GaAs wafers of the kind (a) ‘s-s-s-s’ and (b) ‘s-ss-s’ have been considered where ‘s’ denotes the GaAs wafer of standard thickness s = 0.64 mm and dash represents the air slot of thickness a = 2.50 mm.

Fig. 7.1 shows transmission and reflection spectra (dark red and light green curves, respectively) measured for these structures in the dark in the frequency band f = 75–110 GHz using the VNA test facility at the NUI Maynooth in the comparison with simulation results (c) and (d) obtained for the same structures, respectively, at oblique plane wave incidence at the angle θ = 11 degrees that corresponds to the experimental setup geometry.

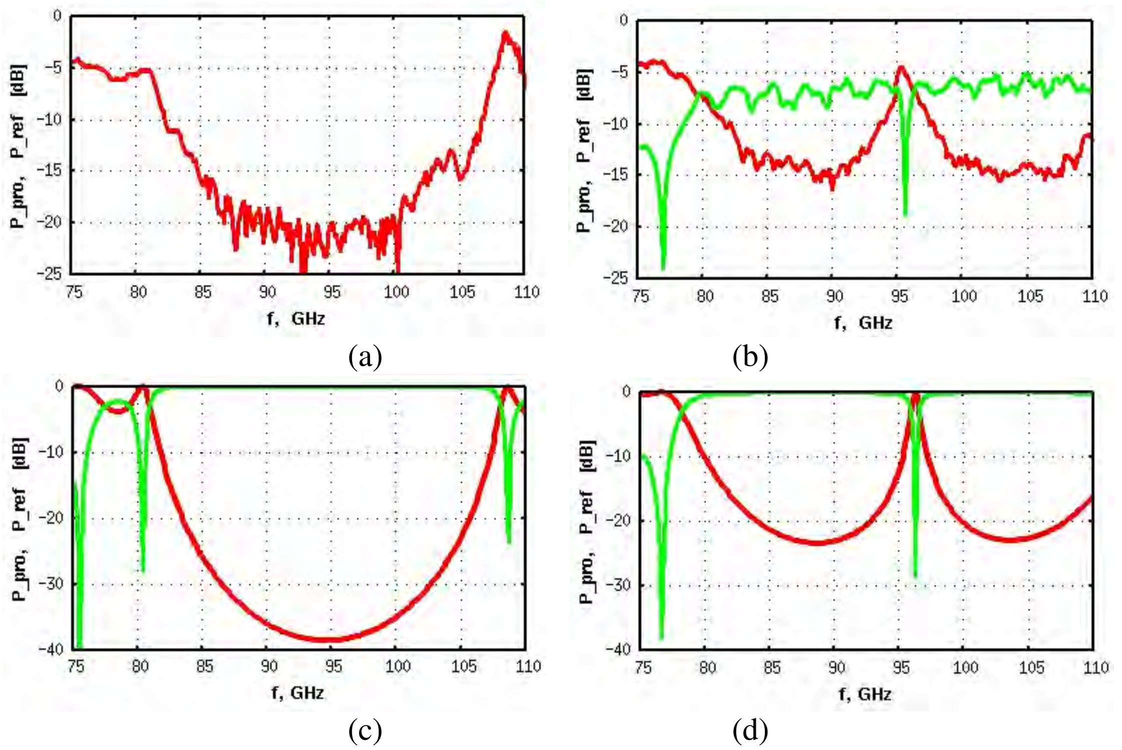
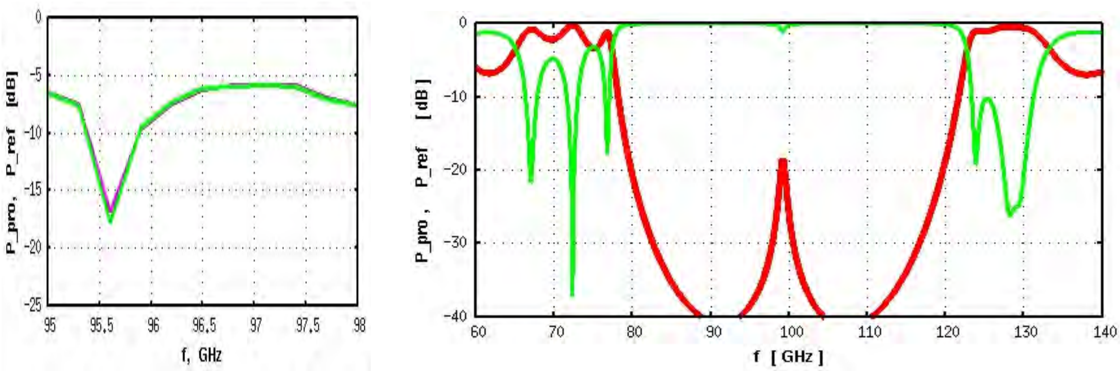


Fig. 7.1. Transmission and reflection spectra (dark red and light green curves, respectively) measured for (a) ‘s-s-s-s’ and (b) ‘s-ss-s’ GaAs structures with air slots a = 2.50 mm and wafer thickness s = 0.64 mm in the frequency band f = 75 – 110 GHz using the VNA test facility at the NUI Maynooth in the dark state in comparison with simulations (c) and (d) for the same structures, respectively, at oblique plane wave incidence at the angle θ = 11 degrees that corresponds to the experimental setup geometry

The most sensitive feature of these spectra is the resonant reflection dip close to the frequency f = 95 GHz in Fig. 7.1, b and d. When testing the dip variation in response to the light pulse of a flash lamp, the difference of about 1dB at the dip level of nearly –18dB can be detected as shown in Fig. 7.2, a.

Since the structure of this kind (an assembly ‘s-ss-s’ illuminated from one side) is not yet the most sensitive one, much higher photo-response should be expected when using other structures, e.g., those simulated in Fig. 6.3. Then, by choosing the light intensity so as to obtain the same 1dB dip variation in a theoretical curve in Fig. 7.1, d, and applying it to the structure simulated in Fig. 6.3, we find that the reflection dip of the structure nearly disappears at this illumination and the transmission peak decreases from 0 to –18dB as shown in Fig. 7.2, b (the conditions above correspond to σ = 60 Sm/m and light intensity $3*10^3$ Suns, i.e., $I = 0.3$ kW/cm^2, if the electron-hole diffusion length is L = 3 micrometers).



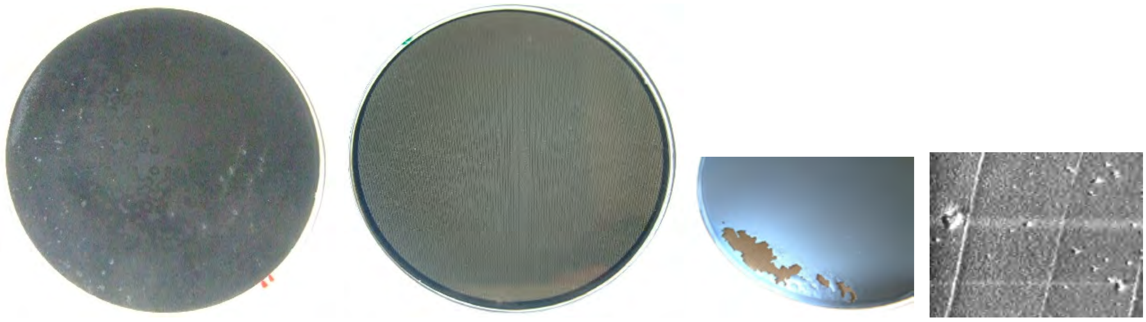
(a) (b)

Fig. 7.2. (a) Reflection spectrum of ‘s-ss-s’ GaAs structure with air slots a = 2.50 mm and wafer thickness s = 0.64 mm measured in the dark state and under the flash lamp pulse illumination (light green and magenta curves, respectively) and (b) reflection and transmission spectra (light green and dark red curves, respectively) computed for the structure of Fig. 6.3 when illumination is chosen to be precisely the same as in Fig. 7.2, a (the one that reproduces magenta curve in (a) when simulations are made for the same ‘s-ss-s’ GaAs structure that yields $I = 0.3$ kW/cm^2)

Thus, the experimental test proves the feasibility of producing mm-wave photonic structures capable of switching quasi-optical beams by the light signals of moderate power generated with available experimental means using inexpensive light sources. The main goal is now to produce and experimentally test the operation performance of these structures that, in addition, may require a certain enhancement of mm-wave beam forming system and, possibly, application of additional short-pulse LED-based dedicated light sources.

7. Experimental Part 2: CdTe Films on Quartz Substrates

Photosensitive CdTe films (Fig. 8.1) were obtained on fused quartz substrates at the Department of Materials for Electronics and Solar Cells, National Technical University "KhPI", Kharkov, Ukraine, by using the closed-volume deposition technique [9-11]. The thickness of CdTe films was chosen to be 4 to 5 micrometers that is optimal for achieving maximum photosensitivity of devices. Fused quartz substrates were of thickness t=0.54 mm and the diameter D=75 mm as required by the design of mm-wave photonic crystals being developed.



(a) (b) (c) (d)

Fig. 8.1. Examples of CdTe films on quartz substrates: (a) CdTe film subject to photo-activation treatment, (b) photo-activated CdTe film coated with molybdenum grid as a top layer, (c) poor adhesion of CdTe film grown on top of molybdenum grid (a sub-layer grid is visible in the faulty area), (d) scanning electron microscopy (SEM) image of grid (grid slots and metal strips are of the width s=0.003 mm and w=0.330 mm, respectively, as required by the design)

Fresh-deposited polycrystalline CdTe films were subject to a special photo-activation treatment that is necessary for obtaining sufficiently high photosensitivity of these structures (Fig. 8.1, a). Metallic gratings of various kinds are supposed to be used on these structures in some cases either for the purpose of making diffraction or polarization gratings, or for possible enhancement of photo-response of these devices. Therefore, some structures were fabricated as CdTe films coated with molybdenum grid as a top layer (Fig. 8.1, b) and some others as CdTe films deposited on top of molybdenum grid used as a sub-layer (Fig. 8.1, c).

Molybdenum was chosen as a grid material for technological reasons. For the same reason, magnetron sputtering has been used as a method of grid deposition. Molybdenum usually makes a good quality interface and electrical contact with CdTe films when used as either the top or the bottom layer. Our experiments revealed, however, certain adhesion problems in some cases when the molybdenum grid is used as a sub-layer (Fig. 8.1, c) whereas Mo grids on top of CdTe films were quite perfect (Fig. 8.1, b).

The adhesion faults may arise due to the height profile of Mo grid under the CdTe film (the height profile can also be seen on the surface of CdTe film in the areas of good adhesion, see Fig. 8.1, c). The problem could be eliminated by optimizing the technology of manufacturing the structure or by varying the kind of material used for the sub-layer grids.

High-frequency (mm-wave) electromagnetic testing of PC structures made with the use of CdTe-coated quartz wafers (see the following Sections) confirmed the appearance of photo-response of CdTe films after photo-activation treatment and no response in the case of no treatment, just as expected. Also, separate wafers with CdTe films were completely transparent for mm-waves both in the dark state and under the illumination tested, thus, proving sufficiently high resistivity and mm-wave impedance of basic CdTe films.

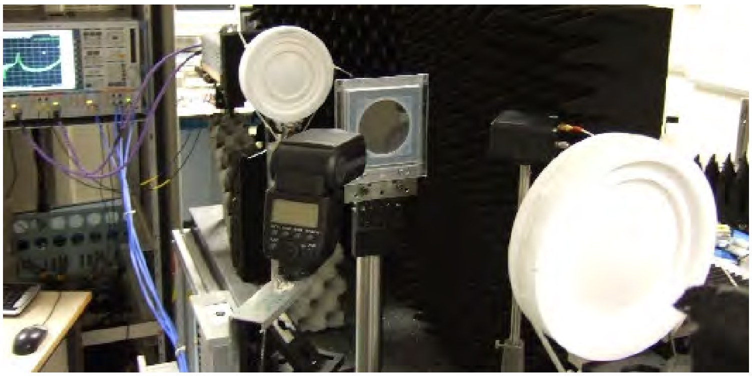
In the meantime, none of the grid structures tested by present, whether it is a sub- or a super-layer grid used with CdTe film, or even the grid with no CdTe coating (Fig. 8.1, d), showed any significant transmission of mm-waves of relevant polarization (when the electric field is orthogonal to the grid strips) but revealed, instead, quite significant back reflection. Though the issue requires further analysis supported by numerical simulations of possible effects of small but finite resistivity of metallic strips that may lead to the resonant wave absorption (the analysis requires the development of a special simulation software enhanced with relevant computational capabilities), there could be a more plausible reason for such a behavior of actual metallic grids.

When examining scanning electron microscopy (SEM) images of grids (Fig. 8.1, d), one can notice that occasional faults in the otherwise continuous metallic strips (seen as small white spots on the gray strip area) have a greater contrast as compared to that of the light narrow lines that correspond to the slots between strips. It means that the slots are not fully free of metal but remain slightly coated with a thin metallic film (though quite non-uniform). It is known, however, that, because of a very small impedance of metal, even an extremely thin metallic film (even of a dozen nanometer thin) would result in significant reflection and, therefore, low transmission of millimeter waves.

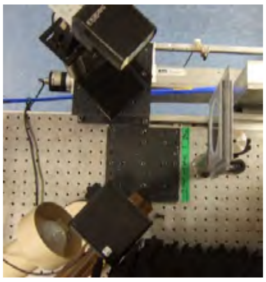
Thus, a possible solution to the issue of low grid transmission (and, therefore, of no positive effects of grids) would be elimination of a thin metallic film in the slots by a suitable etching procedure, by reducing the overall grid thickness during the grid deposition, or by replacing a highly-conductive metal by a much more resistive transparent conductive oxides (TCO) such as indium-tine oxide (ITO), zinc oxide (ZnO) and similar materials.

8. Experimental Part 3: VNA Quasi-Optical Bench Setup

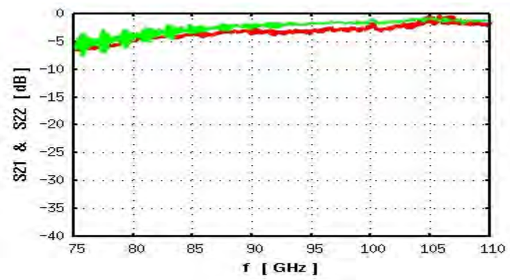
Millimeter-wave electromagnetic testing of PC structures has been made by using a Vector Network Analyzer (VNA) quasi-optical bench facility at the Experimental Physics Department, National University of Ireland Maynooth, Maynooth, Ireland (Fig. 9.1).



(a)



(b)



(c)

Fig. 9.1. VNA quasi-optical bench facility at the NUI Maynooth, Ireland, operating in the frequency range f = 75–110 GHz: (a) a general view of a setup with two coupling lenses, (b) a top view of a sample, stroboscopic flash unit (Canon SL 580 EXII), conventional desk lamp and photodetector, and (c) a reference transmission (dark red) and refection (light green) signal curves (S_{21} and S_{22} scattering matrix coefficients, respectively) measured in the case of beam propagation through lenses with no sample (S_{21}) and with a metallic mirror mounted as a sample (S_{22})

Two aspheric double-sided Fresnel lenses of special design have been developed for the setup with the purpose of accurate conversion of Gaussian beams of the receiver and transmitter feed horns into convergent beams of optimal beamwidth consistent with the sample aperture size D = 75 mm at the spillover level P_S = – 40 dB defined by the level of a signal in the band gap of typical PC.

A high quality of quasi-optical setup is illustrated by the reference transmission (S_{21}) and refection (S_{22}) curves measured in the case of beam propagation through lenses with no sample and with a metallic mirror used instead of sample, respectively (see Fig. 9.1, c).

9. Experimental Part 4: Silicon-based Photonic Crystal Switch

Experimental investigation of light-controllable mm-wave photonic-crystal switches is better to begin with PC assemblies composed of quartz wafers with air spacing as a basic PC and a silicon wafer as a resonant insertion layer. The advantage of these structures is their high sensitivity arising due to a number of essential reasons.

When using low-loss fused quartz and high-resistivity silicon wafers, one would obtain a PC resonator with large quality factor Q at propagation peak. This leads to large increase of light sensitivity of PC. The Q factor is also large because of large dielectric constant of silicon that increases the concentration of mm-wave field at the insertion layer.

Another reason is that silicon, being an indirect-gap semiconductor, has a rather large absorption length of light in a significant fraction of the light spectrum (l ~ 0.1 mm). This makes the effective thickness of photoconductive layer being, at least, that large, which is a hundred times greater than it happens in the direct-gap A3B5 and A2B6 semiconductors such as GaAs and CdTe, respectively. And a greater thickness of photoconductive layer is crucial for the effective blockage of mm-waves when switching off the device by the light pulses.

In addition, silicon, typically, has rather good photovoltaic properties characterized by large electron-hole diffusion (recombination) length L. The latter, in many cases, is also about L~ 0.1 mm (or even more) that corresponds to the electron-hole recombination time τ_R ~ 6 μs (assuming intrinsic silicon). As a result, quite high conductivity could be achieved in a photoconductive layer that makes switching off the devices even more effective.

For all the reasons, silicon-based PC-enhanced quasi-optical mm-wave switches could be made extremely light sensitive, but the price for high sensitivity could be a limited speed of operation (in reality, the operation speed of PC switches requires a special investigation since it should depend on the mode of switch operation). When special measures taken to reduce the recombination time to the level of τ_R ~ 1 ps (e.g., by using radiation damaged intrinsic silicon or beryllium doped GaAs), optoelectronic switches could be made to operate at a very high speed, though they would require more powerful light pulses.

In this work, undoped intrinsic silicon wafers of thickness t_{Si} = 0.50 mm (supplied by El-Cat Inc, USA) and electric fused quartz wafers of thickness t_q = 0.54 mm (Quartz Unlimited LLC, USA) have been used for making the basic test PC structures. The electron-hole recombination length in silicon, as estimated from our measurements of mm-wave switching, was found to be about L ~ 0.3 mm (τ_R ~ 50 μs) that allowed us to demonstrate the effect of PC enhancement of quasi-optical mm-wave switches in full power (Fig. 10.1).

Fig. 10.1 shows that the PC of the kind '5q-si-5q' increases the sensitivity of silicon switch by 20 to 30 dB. The effect is so strong that even a conventional incandescent 100W desk lamp can reduce the device transmission at the propagation peak at f=92.5 GHz by 15dB whereas the light pulse of peak intensity estimated as 0.4 W/cm^2 (about 4 Suns at 45^o upward tilted light-head of the flash lamp) can completely cut off the propagation peak in the band gap down to –30dB (blue curves and dots in Fig 10.1, c and d). For the comparison, light intensity at horizontal light-head estimated as ~11 W/cm^2 (about 110 Suns) blocks mm-wave propagation in the entire band gap down to –60 dB and below.

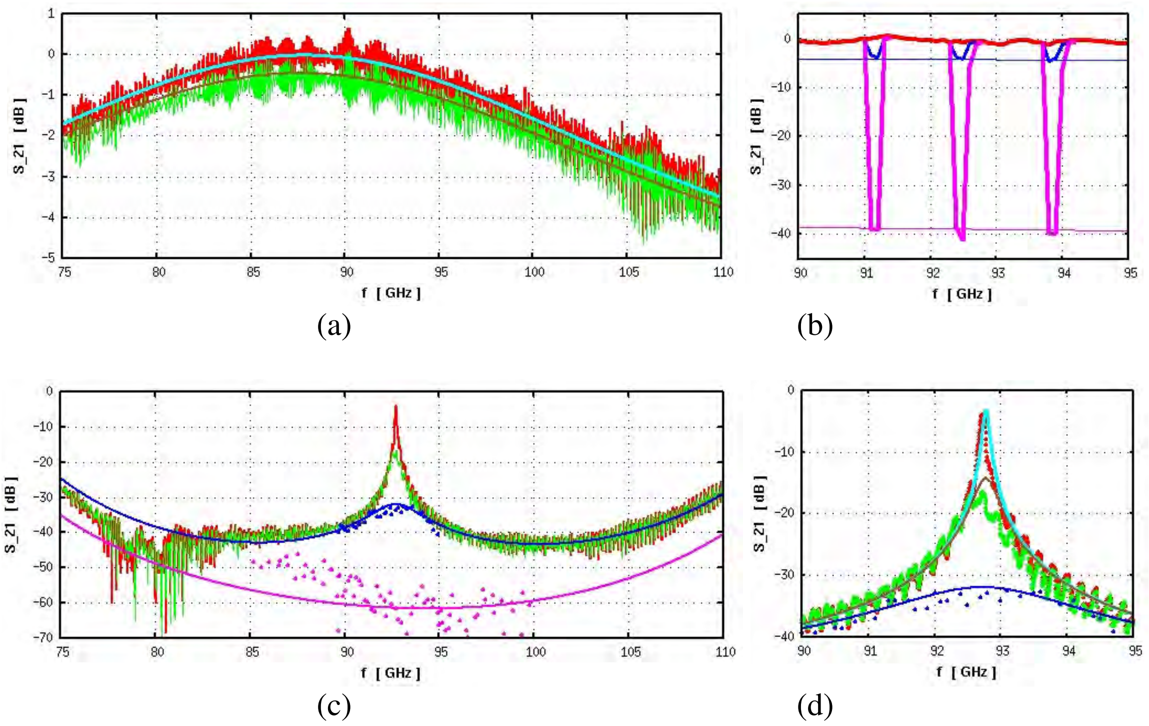


Fig. 10.1. MM-wave transmission spectra of (a, b) Si wafer and (c, d) quartz-air PC with a Si wafer insertion (PC of the kind '5q-si-5q' with air slots a = 0.52 mm) which show measurement results obtained in the dark (red curves) and under three kinds of illumination – by a 100W desk lamp (green curves) and stroboscopic flash unit (Fig. 9.1) at horizontal (thick magenta curves and dots) and 45^o upward tilted light-head (thick blue curves and dots) – against computer simulations (thin smooth curves of relevant kinds)

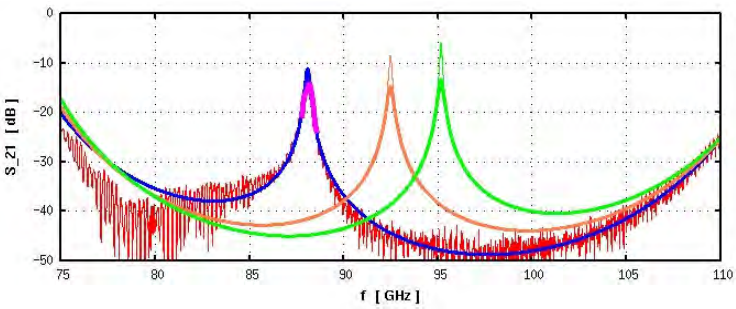
A remarkable feature of the results is that matching all simulations to the experiment requires virtually no fitting parameters. In fact, the only two parameters that needed any adjustments were the recombination length (see above) and the coefficient accounting for the fact that the light power entering a Si wafer in the PC seems to be about 25-30% of that entering a free-standing Si wafer under all three kinds of illumination considered.

10. Experimental Part 5: CdTe-based Photonic Crystal Switch

CdTe-based optoelectronic switches promise a number of advantages over alternative devices. As a direct-gap semiconductor with a small light absorption length l ~ 1 μm, CdTe can be used in the form of thin-film structures deposited on various kinds of substrates. Because of small recombination time ($\tau_R = 10^{-8} - 10^{-12}$ s), CdTe can be applied for making ultra-fast switches and other devices. Finally, CdTe is more technologically acceptable as compared to other materials such as GaAs and similar compounds.

In this work, CdTe optoelectronic switches utilize CdTe films deposited on fused quartz substrates. When using available quartz wafers of thickness q = 0.54 – 0.56 mm, an optimal quarter-wavelength quartz-air PC would have air slots a = 1.05 mm that corresponds to the band-gap mid-frequency f = 71.2 GHz (wavelength $\lambda = 4a$ = 4.21 mm). In this case, an optimal PC with a resonant half-wavelength insertion layer would be of the kind as shown in Fig. 5.2 (a structure with a double-wafer insertion) which should have transmission and reflection spectra as computed in Fig. 4.1.

In practice, in order to meet experimental requirements of matching the frequency band of VNA facility (f = 75–110 GHz), PC structures with triple-wafer insertion layers (equivalent of one-wavelength thickness at the transmission peak frequency) and air slots of size a = 0.52 mm have been used. The structures of this kind possess the transmission spectra with resonant transmission peaks as shown in Fig. 11.



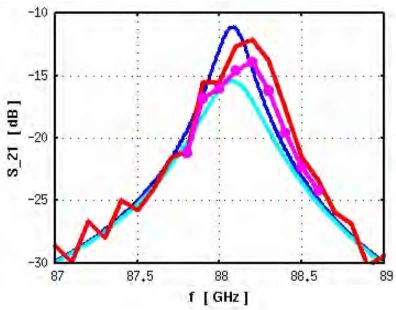
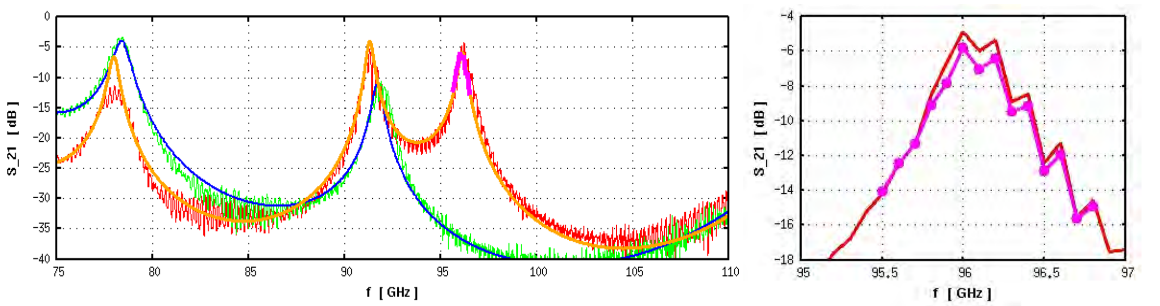


Fig. 11.1. Measured (red and magenta curves) and computed transmission spectra of CdTe-based PC structures '5q-qvqvqs-5q' with air slots a = 0.52 mm, fused quartz wafers q = 0.54–0.56 mm, CdTe films s = 0.004 mm and small spacers v = 0.1, 0.05 and 0 mm (blue, amber and green curves, respectively) in the dark (experimental red and simulated dark-blue and thin green and amber curves) and under illumination by stroboscopic flash lamp at horizontal light-head position (simulated thick green and amber curves in (a), light-blue curve in (b), and measured magenta curves in (a) and (b))

For obtaining a certain control over transmission peak frequency position f_o, small spacers of thickness *v* have been introduced between the insertion wafers that allowed us to shift the transmission peak within the PC band gap as shown in Fig. 11.1, a. Because of finite mm-wave losses, transmission peak decreases with increasing the number of wafers in the PC. An optimal number of quartz wafers on each side of insertion layer varies from 3 to 5. In each case, however, the effects of light pulses remain comparable.

Variation of transmission peak in response to light pulses is shown in Fig. 11.1, b. In this case, the front surface of triple-quartz-wafer insertion is coated by 4 μm CdTe film subject to photo-activation process. As one can see, the transmission peak is reduced by about 1 dB in magnitude due to illumination at the maximum pulse intensity used in experiments. This is a much smaller effect as compared to the one observed in Si-based PC structures above (notice, neither smaller light intensity, no molybdenum grids made so far, nor CdTe films without photo-activation produce any noticeable effect in response to light pulses).

For the comparison with other PCs of similar characteristic properties, two cases of quartz-air PC structures with GaAs twin-wafer insertion of the kind '4q-sgvgs-4q' have been tested (Fig.11.2). Here, 'g' is the GaAs wafer of thickness g = 0.64 mm, 's' and 'v' are extra air spacers, and '4q' symbolize 4-layer quartz-air PC sections of the same kind as considered above in both the CdTe- and Si-based structures.



(a) (b)

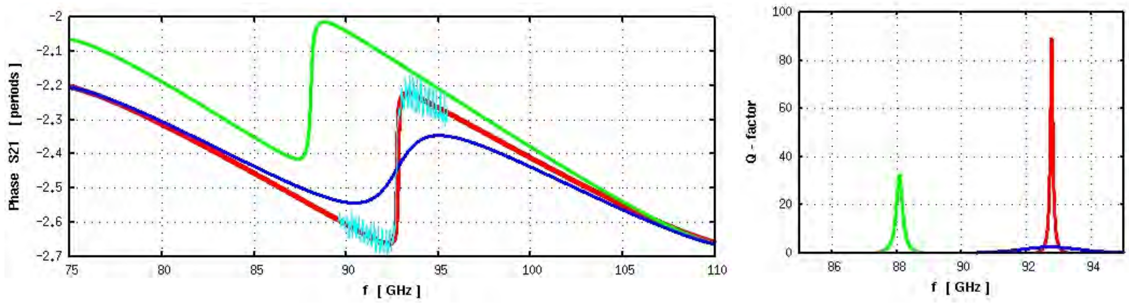
Fig. 11.2. Measured (red, green and magenta curves) and computed (blue and amber curves) transmission spectra of quartz-air PC '4q-sgvgs-4q' (q=0.55mm, a=0.52mm) with GaAs ('g') twin-wafer insertion (g=0.64 mm) and extra spacers (s, v) in the dark (red/amber and green/blue curves at s=1.60mm, v=0.24mm and s=0.29mm, v=0.19mm, respectively) and under illumination by stroboscopic flash lamp at horizontal light-head position (magenta curves with circular points which correspond to different light pulses)

PC structures of this kind are far from optimal for the effect considered, though simulations match the experiment pretty well. In this case, the light effect remains of similar small magnitude (about 1 dB) as in the case of CdTe-based structures. The main reason is a non-optimal kind of structures in use, with extra spacers being made due to manufacturing reasons that results in splitting a single highly-sensitive transmission peak into pair of peaks of reduced sensitivity (once all simulations match the experiment so well, one can be sure that the ideal structures would behave as shown in Fig. 6.3 above).

A general physical reason for low sensitivity of both the CdTe and GaAs structures as compared to silicon-based PC is a small recombination length in CdTe and GaAs materials. Yet, both the structures could be made more sensitive should the losses in quartz wafers be reduced. An estimate shows that wafers in use may have a loss tangent at 100 GHz of about 0.01 whereas better values are possible when using a good quality electrically fused quartz.

A graphical illustration of PC quality is presented by the quality factor Q of structures considered as open resonators (Fig. 11.3). The Q factor can be found by computing mm-wave photon lifetime τ as the derivative of the phase of transmission wave (Fig. 11.3, a) over the frequency [13, 14]. Then, using the definition of Q as $Q=W/\Delta W$ where W is the energy stored in the resonator and ΔW is the energy loss per one period of oscillation, we can find Q factors for different structures as shown in Fig. 11.3, b.

As one can see, Q factor of silicon-based PC at the transmission peak frequency f_0=92.5 GHz is about Q=90 in the dark whereas Q of CdTe-based PC is only Q=36 that makes CdTe-based structures less sensitive switches as compared to Si-based PCs.

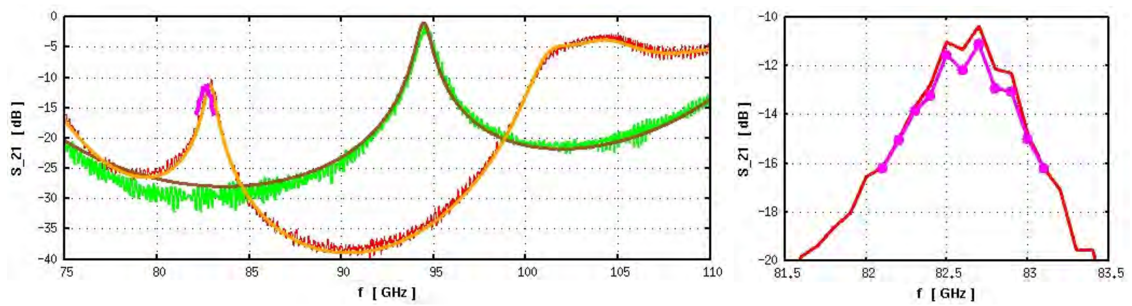


(a) (b)

Fig. 11.3. (a) Phase of transmission wave (in units of oscillation period) and (b) Q-factor of a Si-based PC of Fig. 10.1 (c and d) in the dark (computed red and measured light-blue curves) and under flash lamp illumination at 45^o tilted light-head (dark-blue curves) and CdTe-based PC of Fig. 11.1 (b) in the dark (green curve)

As an alternative to quartz-air PC structures, other possibilities have also been investigated, of which a suitable option is the plastic-air PC where plastic layers of PVC, acetate and other transparent materials could be used (Fig. 11.4).

Plastic-air PC structures, despite, possibly, lower Q factors due to, generally, lower values of dielectric constant and higher dielectric losses as compared to quartz, may provide other advantages. One of them is the fact that quartz wafers are rather fragile and could not



(a) (b)

Fig. 11.4. Transmission spectra of plastic-air PC with CdTe-coated triple-quartz-wafer insertion of the kind '6t-qvqvqs-6t' (computed yellow and measured red and magenta curves) and quartz-air PC of the kind '3q-sqqq-3q' (computed brown and measured green curves) where plastic plates (acetate) of thickness t = 0.72 mm and air slots a = 0.37 mm have been used in the first case (red and magenta curves correspond to the same dark-state and light-pulse illumination conditions as in Figs. 11.1 and 11.2 above)

withstand significant accelerations and vibrations. Another advantage is that, in certain cases, CdTe films could be deposited on plastic as well (e.g., on polyimide films) that allows one to completely exclude fragile components from the PC switch.

As an example, Fig. 11.4 shows the light effects observed in a CdTe-based PC of the kind '6t-qvqvqs-6t' where 't' represents the acetate sheets of thickness t=0.72mm used in combination with an air slots a=0.37mm (red and amber curves in Fig. 11.4, a and b) and q, v, and s represent the same kinds of quartz wafers, air spacers, and CdTe films, respectively, as those considered in Fig. 11.1.

Plastic PC of this kind, though not yet perfectly optimized for the given effect, appears also to be light sensitive at about the same level as quartz-air PCs considered above. This opens a possibility of further enhancement of these structures for the potential use as light-controllable mm-wave beam switchers.

11. Conclusions

Frequency-selective mm-wave photonic-crystal (PC) beam switches of increased sensitivity for rapid turning off and on quasi-optical beams in response to light pulses as control signals have been designed, manufactured and experimentally tested.

Light-controllable PC-enhanced devices using semiconductor wafers (semi-insulating GaAs and Si layers or CdTe-coated quartz plates) with special surface patterning will provide additional functionality for mm-wave beam processing, with sensitivity improved, according to simulations, by 2 to 4 orders of magnitude as compared to a single-wafer device.

Experimental testing of light sensitivity of different kinds of PC structures when using a flash lamp as a light source proved a possibility of making mm-wave PC devices capable of switching quasi-optical beams with available inexpensive light sources.

Quartz-air PCs with a Si wafer insertion have shown extreme sensitivity due to slow electron-hole recombination (τ_R~50μs) and thick photoconductive layer in silicon (L=0.3mm) that allows one to completely turn off the transmission peak at f = 92.5 GHz by the light pulse of intensity I ~ 0.4 W/cm^2 (the PC transmission peak is reduced by 30 dB in response to the light whereas a single Si wafer transmission drops only by 4 dB).

Similar kinds of PCs using CdTe-coated quartz wafer insertions, likewise GaAs wafers, are less sensitive to the light due to small recombination length (L ~ 3 μm) in CdTe and GaAs. Yet, a flash lamp illumination proved to be sufficient for observing a reduction of transmission peak of PC.

Use of CdTe-coated quartz wafers and, even more so, plastic PCs and CdTe films on flexible substrates, promises essential advantages over conventional design solutions that makes it worthwhile to extend the developments in this direction. Use of surface patterning should also increase the light sensitivity of devices that requires further improvements in the technology of CdTe films with various kinds of metallic patterns.

Thus, due to high quality of PC structures at mm-waves and special methods of surface impedance optimization, the PC-based devices can be made to operate at a reduced light intensity avoiding the use of powerful lasers that makes them more suitable for practical applications.

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List of Symbols, Abbreviations, and Acronyms

f is the mm-wave radiation frequency

Q is the resonator quality factor

D is the device aperture diameter

$tan(\delta)$ is the mm-wave loss tangent of the material

q, t, t_q are the values of quartz wafer thickness

t_{Si} is the Si waver thickness

g is the GaAs wafer thickness

s is the semiconductor film (CdTe) thickness

s, w are the widths of air slots and metal strips in metallic grids

a is the air slot between wafers

I is the light intensity

Zs is the surface impedance of the material

Zo is the impedance of the free space

T is the temperature

e is the electron charge

L is the electron-hole diffusion (recombination) length

l is the light absorption length

σ is the electrical conductivity of the material

ε is the dielectric constant of the material

θ is the incidence angle of mm-wave beam

τ is the mm-wave lifetime in a photonic crystal

τ_R is the electron-hole recombination time in a semiconductor

v, s are the air spacers in certain kinds of PC

S_{21} , S_{22} are the scattering matrix coefficients

P_S is the mm-wave beam spillover level at the PC aperture

W is the energy stored in the resonator

ΔW is the energy loss in the resonator per one period of oscillation

Acknowledgement of Sponsorship: Effort sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under grant number FA8655-10-1-3086. The U.S. Government is authorized to reproduce and distribute reprints for Government purpose notwithstanding any copyright notation thereon.

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Disclosure of Inventions: I certify that there were no subject inventions to declare during the performance of this grant.