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LED-Array Light-Controlled Photonics-Enhanced MM-Wave Beam Switch

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Özet: *Bu bildiride, 75-110Ghz mm-dalga bandı rezonans frekanslarda çalışan, ışıkla kontrol edilen ve fotonik kristal ile iyileştirilmiş quazi-optik mm-dalga hüzme anahtarın deneysel incelenmesi sunulmaktadır. Sözkonusu anahtarlar rezonans kusur-katmanlı yüksek dirençli Silikon ile dielektrik Bragg yapı olarak gerçeklenmiştir. Bu yapı mm-dalga propagasyon boşluğunda seçilen frekansta çok dar transmisyon tepesi yaratmaktadır. Tepe genlik değeri yapıyı aydınlatan ışık darbelerinin şiddetine duyarlıdır.30KOhm*cm direnç gösteren Silikon katman ve 400W LED dizi ışık kaynağı kullanarak, yaklaşık 20dB transmisyon tepe modulasyonu elde edilmiştir.*

Abstract: *We present experimental investigation of light-controlled photonic-crystal-enhanced quasi-optical mm-wave beam switches operating at a resonant frequency in the mm-wave band of 75 to 110 GHz. The switches are implemented as dielectric Bragg structures with a resonant "defect layer" of high-resistivity silicon that creates a narrow transmission peak at the chosen frequency within the mm-wave propagation gap. The peak amplitude is sensitive to the intensity of light pulses illuminating the structure. When using a silicon wafer of 30 KOhm*cm resistivity and the light pulses created by a 400W LED-array light source, we achieved mm-wave transmission peak modulation of about 20 dB .*

1. Introduction

Optical control of THz and sub-THz quasi-optical beams is a promising way of ultra-fast switching, modulation, and other kinds of processing of electromagnetic waves of millimeter (mm) and sub-millimeter (sub-mm) wave bands [1-3]. In this way, e.g., a nanosecond-fast light-controlled phase inversion in a 30GHz quasi-optical beam is achieved [1] using the photoconductivity effect in a silicon wafer placed on top of metallic mirror. The effect, though, requires a high-power Ti:sapphire laser whose radiation has to be re-focused over the entire silicon surface.

Light sensitivity could be enhanced through the use of quasi-optical resonators with photoconductive elements that control the wave propagation. Ref. [2] presents a THz device with enhanced sensitivity due to the use of Bragg structure with GaAs inner layer as a photoconductive element. The structure works as a beam switch that controls propagation of 0.6 THz radiation by means of ultra-short optical laser pulses. The device operates as a one-dimensional photonic crystal (PhC) with GaAs core as a resonant "defect" layer. The THz electric field is enhanced in the photonic structure at the surfaces of the GaAs layer. Due to small wavelength of THz beam and small size of structure, the laser beamwidth is also small. The response time of the element to pulsed photoexcitation is about 130 ps, which is nearly 80 periods of oscillations in the THz wave beam. Further possibilities in the optical control of THz beams are shown in Ref. [3]. The authors demonstrate photo-conductive gratings created on a GaAs surface by femtosecond laser for the manipulation of THz waves. The high-contrast pattern of photo-excited carriers can create dynamical diffractive elements, thus, providing a route to THz components with reconfigurable functionality.

All the devices above require high-power lasers for their operation. While it is a necessity for ultra-fast devices, this creates limitations in experimental research on physical effects in light-controlled systems, optimization of design and functionality of devices, development of more efficient kinds of structures, and in those cases when slower but more sensitive switches are preferable.

The aim of this work is to present the experimental implementation of mm-wave quasi-optical beam switch controlled by the LED array light pulses easily created with inexpensive laboratory equipment.

2. Bragg Structures with Resonant Transmisson

Using Bragg structures with resonant transmission is a practical way of making PhC-enhanced light-controlled quasi-optical switches for mm-wave beams. A structure of this kind uses a built-in defect layer of low-loss semiconductor (e.g., high-resistivity silicon wafer) that creates a narrow transmission peak at a certain frequency within the mm-wave propagation gap. The peak amplitude is extremely sensitive to the light intensity, with sensitivity increasing while increasing the quality-factor (Q-factor) of the structure acting as a resonator at the given resonant frequency.

For obtaining the band gap and propagation peaks in the frequency band of 75 to 110 GHz, we used Bragg structures made of the fused quartz wafers separated with air slots of relevant size (typically, about 0.5 mm) and having a defect layer of high-resistivity silicon of similar thickness. Using a silicon wafer with resistivity of 30 KOhm*cm allowed us to obtain the Q-factors of structures at the level of Q ~ 550 at the resonant transmission peak around 90 GHz in the propagation gap covering the band of 75 to 110 GHz when the air slots were about 0.5 to 0.7 mm (for the comparison, an estimate for 0.6 THz structures in [2] shows Q ~ 36).

High resistivity of silicon is also linked with high photoconductivity due to large recombination lifetime. The latter is a limiting factor in the recovery of mm-wave propagation after the light pulse, though it does not hamper the speed of turning off the beam in response to the light pulse emergence.

An essential component of the experiment is the mm-wave quasi-optical bench based on a 75-110 GHz vector network analyser (VNA) available at the Experimental Physics Department of the Maynooth University (NUIM, Ireland). The bench is equipped with dedicated double-sided split-step dual-aspheric mm-wave Fresnel lenses [4] which were specifically designed for the optimal operation of the setup (Fig. 1).

Having the structures of high quality allowed us to achieve an efficient blockage of mm-wave beam propagation with light sources eagerly available around including 100W visible light and 250 infrared incandescent lamps, 100W LED arrays, and common photo-flash lamps. The experiments of this kind are complementary to the other experiments concerning the whispering-gallery-mode resonators [5] which have been made of the same wafers for the purpose of alternative investigations in this area.

3. High-Power LED Array as a Light Source

For the convenience of experimenting with light-controlled mm-wave beam switches, we developed a dedicated light source of high intensity for those cases when extra power and shorter duration of light pulses are needed. For these cases, we designed and fabricated inexpensive 400W LED array light source composed of Chip-on-Board (COB) LED modules that are eagerly available at 100W power per chip.

The source is made as a top-frame assembly of the COB LED modules that matches the geometry of Bragg structures used in our light-controlled experiments (see Fig. 1). The power of the source was found to be optimal for studying the mm-wave beam switches when using the Bragg structures described above.

(a) (b)

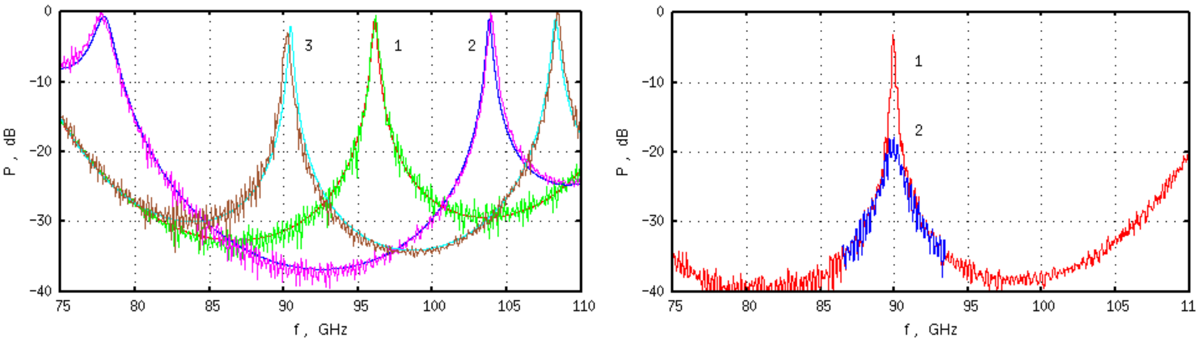
Figure 1. (a) High-power LED array light source (shown at the minimum brightness) and (b) W-band quasi-optical setup used for the light-controlled mm-wave experiments at the NUI Maynooth, Ireland.

4. Light-Controlled Si-Based PhC-Enhanced MM-Wave Switches

We measured transmission and reflection spectra of different kinds of Bragg structures and their response to the light signals of different intensity (Fig. 2). The results confirm sufficient sensitivity of the resonant transmission peaks of defect-layer Bragg structures being used. They show a possibility of optical switching mm-wave beam propagation through the structures at the chosen resonant frequency with the light flux provided by the LED array presented above.

The peak modulation approaching 20 dB is accessible with the given structures. This makes it possible further investigation of the effect for designing the other kinds of structures suitable for the operation under different illumination conditions. The frequency position of transmission peak obtained with available wafers could be varied within the band gap by introducing some extra air space between the inner semiconductor wafer and the outer sections of the Bragg structure surrounding the inner resonant layer. In practice, a set of four quartz wafers on each side of a semiconductor layer (with relevant air slots between wafers) is optimal for the best operation of the entire setup.

The measurements of this kind could provide the information on the mm-wave characteristics of various materials used in the design. As an example, when using three kinds of Bragg structures with a defect layer made as a set of one, two, or three quartz wafers instead of a silicon wafer, we could evaluate, to a relatively high accuracy, the dielectric characteristics of quartz wafers being used. Specifically, we found the relative dielectric constant of wafers to be $\varepsilon_r = 3.83$ and the loss tangent $\tan\delta = 0.001$.



(a) (b)

Figure 2. Transmission characteristics of Bragg structures with account of reference signals: (a) three kinds of quartz structures in comparison to simulation results and (b) light-sensitive transmission peak of a Si-loaded structure at the frequency $f = 90$ GHz when measured (1) in the dark and (2) under the illumination from a warm-white 400W LED-array source described above at the LED voltage $V = 36$V.

5. Conclusions

We developed light-controlled photonic-crystal-enhanced quasi-optical mm-wave beam switches operating at the resonant frequencies in the mm-wave band of 75 to 110 GHz. The structures are made as the Bragg structures assembled of the fused quartz wafers with a resonant defect layer of high-resistivity silicon that creates a narrow transmission peak at a certain frequency within the mm-wave propagation gap. The structures are controlled by a dedicated 400W LED array light source. A resonant mm-wave transmission peak modulation approaching 20 dB has been achieved with these structures in response to the LED array light pulse excitation.

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