

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Terahertz spatial light modulator with digital microfluidic array

Péter Földesy^{a,*}, Zoltán Fekete^b, Tamás Párdy^{b,c}, Domonkos Gergelyi^{a,c}

^aCellular Sensory and Optical Wave Computing Laboratory, MTA-SzTAKI, Kende utca 13-17, Budapest, 1111, Hungary

^bInstitute for Technical Physics and Materials Science, MTA-TTK, Konkoly Thege út 29-33, Budapest, 1525, Hungary

^cFaculty of Information Technology, Pázmány Péter Catholic University, Práter utca 50/a, Budapest, 1083, Hungary

Abstract

We propose a radically different idea for spatial light modulation in broadband terahertz range compared to existing solutions. We utilize the high and broadband absorption of water for THz spatial modulation by means of programmable digital microfluidic droplet array. The structure is transparent in the THz region as it has coplanar electrode arrangement without conducting top electrode. The array has two reservoirs to work as a closed system to move around droplet arrangements. A microfluidic chip has been manufactured to be used in reflective setup. This proof of concept is presented here including a 10x10 array demonstrated at 0.48THz with near 100% contrast. The possible usage of the solution is e.g. imaging using compressed sensing. The architecture is applicable to droplet spectral analysis as well due to its transparent top plate.

© 2012 The Authors. Published by Elsevier Ltd. Selection and/or peer-review under responsibility of the Symposium Cracoviense Sp. z o.o. Open access under [CC BY-NC-ND license](#).

Keywords: Terahertz, spatial light modulation, digital microfluidics;

1. Introduction

Generally, the Terahertz (THz) spatial waveform modulators are able to control the transmission of an incident terahertz wave. Moreover, beam steering and focusing is also reachable by two dimensional arrays of beam modulators. The monolithic integrated spatial modulators offer high modulation rate up to several megahertz, while usually limited to a certain resonant frequency or range with a limited switching value significantly less than 100%. Such modulators are the electrically-driven terahertz metamaterial spatial modulators [2-3] and reconfigurable metallic slits [4]. Solid state THz detector arrays are integrated in individual dies with a limited number of detectors per die due to the relatively long wavelength (0.1–3 mm). The spatially modulated illumination is a possibility to increase this spatial

* Corresponding author. Tel.: +36-1-249-6249; fax: +36-1-249-6249.

E-mail address: foldesy@sztaki.hu.

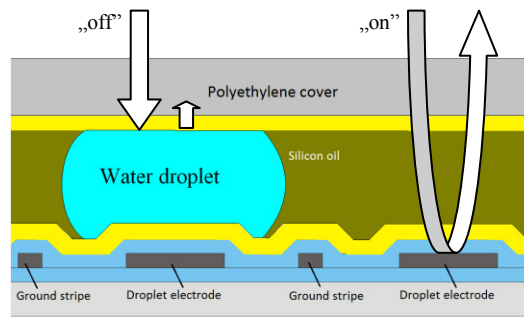


Fig. 1. Illustration of the modulation principle using highly absorptive water droplets and the cross-section of the coplanar microfluidic structure.

resolution in far field and near field cases (e.g. imaging using compressed sensing [1] or resolution enhancement by structured light). Our proof of concept chip has been chosen from this field.

1.1. Droplet based modulation

The droplet and electromagnetic wave interaction has been utilized before in different contexts e.g. as dye laser frequency tuning architecture [9] and for material analysis [5]. We propose to utilize the high absorption of water for THz spatial modulation by means of programmable digital microfluidic droplet array. The water in liquid and vaporized form has high absorption coefficient with increasing value from 0.02 THz to 30 THz with several peaks. In the investigated sub-THz region this value varies in the range of $50\text{--}100\text{ cm}^{-1}$ with several peaks, which means that a few hundred μm water film constitutes almost total absorption [5]. Our solution takes advantage of this phenomenon by using droplets to create “off” states in a controlled volume, thickness, shape, positioned in a regular rectangular grid. The platform of droplet positioning and movement is the droplet-based digital microfluidics. In digital microfluidics [7], discrete fluidic droplets are translated, mixed or stored on the surface of an array of electrodes. These metallic structures are embedded in between two hydrophobic insulator layer. The working principle of the droplet manipulation is the electrowetting on dielectric (EWOD) [7]. The common solution is to form two layers of hydrophobic substrates, in which the bottom plate is patterned by an array of controllable electrodes and the top plate is coated with grounding electrode. In our scheme, the top electrode must remain “transparent” to the THz radiation, hence a conductive electrode cannot be mounted. Such structure of single electrode plate is called co-planar structure [6-7] with customized ground electrode system on the bottom plate only. Though the activation is higher than in the two conducting layer structure, the transparency is reached. The concept of modulation can be seen in Fig. 1.

1.2. Modulation limiting factors and perspectives

The drawbacks of the concept come basically from the fact, that macroscopic material movement takes place. The droplet size can vary in a wide range, depending on the electrode size. The achievable actuation speed mainly depends on this size, actuation potential, and droplet aspect ratio (droplet size/gap height). Scaling can be maintained as long as the aspect ratio is maintained and droplets could be as small as a few $10\text{ }\mu\text{m}$ [8]. The actuation speed is limited as well to around 100 Hz. On the other hand, the pixel acquisition speed of THz detectors or spectral analyzers used in imaging setups is in pair with this value.

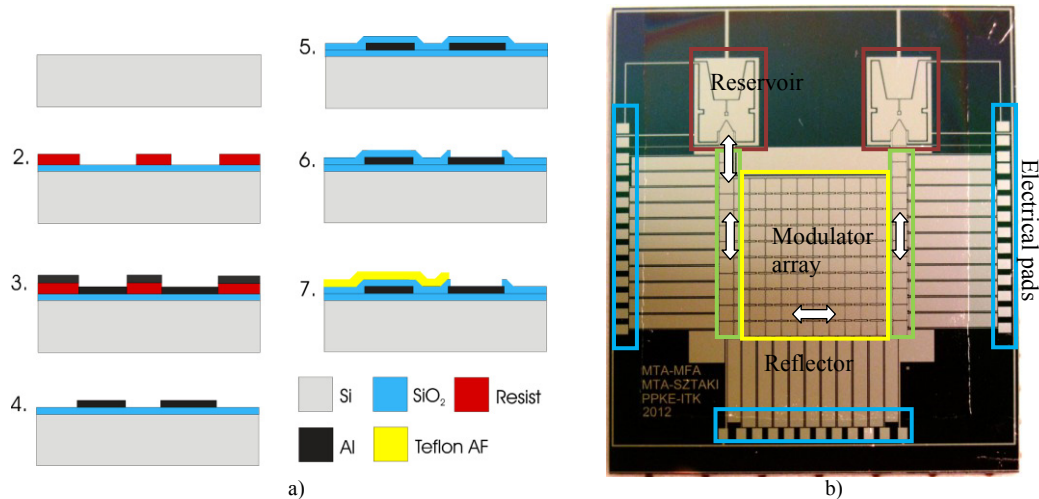


Fig. 2. Schematic process flow of the fabrication of digital microfluidic chips (a). On the right (b), the 10x10 modulator array is shown. The vertical stripes and horizontal array are capable of directional movement as the arrows illustrate. The reservoirs and the U shaped padding can be seen too.

2. Microfluidic chip implementation

The array was realized by silicon micromachining technology. The schematic view of the process sequence is illustrated in Fig. 2a. The initial substrate was <100> single-crystalline silicon wafer. On the bulk silicon, 1000 nm thick thermally grown silicon-dioxide layer was applied (step 1). The electrode system was formed by lift-off technology (step 2-4). 300 nm thick aluminum film was deposited by e-beam evaporation (step 3) and was patterned by conventional photolithography (step 4). The dielectric layer of the microfluidic chip is composed of silicon-dioxide and subsequently developed Teflon AF layer. 100 nm silicon-dioxide was deposited by LPCVD process from silane and oxygen at a temperature of 435°C (step 5). The oxide was removed from the electric contact pads by buffered HF (step 6). Finally, 500 nm Teflon AF was spin-coated on the chip and dehydrated at 165°C on hot-plate to form a hydrophobic top layer (step 7). The top electrode of polyethylene is also covered with thick Teflon AF. The manufactured chip is shown in Fig. 3b. The electrode pitch is 1700 μm with 100 μm gap, while ground lines in the gap are 20 μm wide. The droplet height was set in the experiments to 500 μm . In spite of the fact, that the ground stripes are also covered by silicon-dioxide and hydrophobic layer (in contrast to co-planar structure [6-7]), the chip enables very low voltage and stable operation ($\sim 60\text{-}70\text{V}@10\text{KHz}$).

3. Measurement results

The droplet translation architecture of the sample chip is designed for compressed sensing imaging applications. This imaging method is based on consequent randomly patterned illumination [1]. First, one of the reservoirs is filled and closed and the vertical chain is driven to form a 1D droplet sequence. Next, the modulator array is used to move the shifted droplets horizontally towards the opposite side. These two steps are repeated, and the array is filled with changing sparse and orthogonal patterns (the fill factor is less than $1/9^{\text{th}}$ in order to avoid droplet collision). The vertical chain of the other side is utilized to collect the droplets and store in the reservoir. Later on the direction of flow is changed to backward. The application platform can be seen in Fig. 3a, where a continuous wave VDI sub-THz source provides

illumination in a quasi-optical setup. The sensor is a complex integrated CMOS based sensor with embedded amplification, lock-in detection and digital output streaming [10]. For characterization purposes several droplet arrangements have been raster-scanned with focused beam (Fig. 3b,c shows a two droplet scan at 0.48 THz). The droplets above near three free-space wavelength actuates as diffraction-limited near perfect black region, while the rest of the array had near complete reflection.

Acknowledgements

The work is supported by the Hungarian Scientific Research Fund - OTKA-NIH CNK-77564.

References

- [1] Chan, W.L. and Moravec, M.L. and Baraniuk, R.G. and Mittleman, D.M., Terahertz imaging with compressed sensing and phase retrieval, *Optics Letters* 33 (2008) 974-976
- [2] Paul, O. and Imhof, C. and Reinhard, B. and Zengerle, R. and Beigang, High speed terahertz modulation from metamaterials with embedded high electron mobility transistors, *Opt. Exp.*, 19 (2011) 9968-9975
- [3] Cich, M.J. et al., A spatial light modulator for terahertz beams, *Applied Physics Letters*, 94 (2009) 213511
- [4] S. Zarei and M. Jarrahi, Broadband terahertz modulation based on reconfigurable metallic slits, *IEEE Photonics Society Winter Topicals Meeting Series*, (2010) 30-31
- [5] George, P.A. and Hui, W. and Rana, F. and Hawkins, B.G. and Smith, A.E. and Kirby, B.J., Microfluidic devices for terahertz spectroscopy of biomolecules, *Opt. Exp.*, 16 (2008) 1577-1582
- [6] Li, Y. et al., Test structure for characterizing low voltage coplanar EWOD system, *IEEE Transactions on Semiconductor Manufacturing*, 22 (2009) 88-95
- [7] A.R. Gao et al., A Low Voltage Driven Digital-Droplet-Transporting-Chip by Electrostatic Force, *Chinese Physics Letters*, 28 (2011) 084706
- [8] Das, T. and Chakraborty, S., Bio-Microfluidics: Overview, *Journal of Microfluidics and Microfabrication*, (2010) 131
- [9] Kuehne, Alexander J. C. et al., A switchable digital microfluidic droplet dye-laser, *Journal Lab Chip*, 11 (2011) 3716-3719
- [10] Földesy, P. and Gergelyi, D. and Fuzy, C. and Karolyi, G., Test and configuration architecture of a sub-THz CMOS detector array, *IEEE 15th Symp. on Design and Diagnostics of Electronic Circuits and Systems (DDECS)*, (2012) 101-104

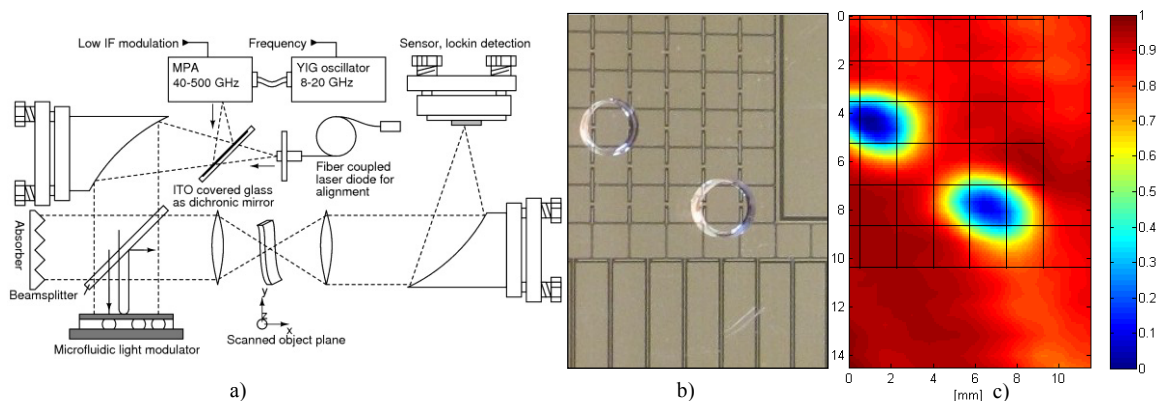


Fig. 3. Optical setup in structured illumination application (a). Visual (b) and raster scan of two droplets in the array at 0.48 THz ($\lambda = 620 \mu\text{m}$) by focused irradiation (c) (spot size FWHM was 2.2 mm). The array pitch is $1700 \mu\text{m}$, while the droplets had near 2 mm diameter.