Multiband THz detection and imaging devices

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ABSTRACT

Terahertz imaging finds more and more applications in homeland security, medical, and life sciences applications. While THz sources and detection systems are gaining ground, the ability of electronics conversion systems to keep up with the development of these systems seems to be lagging behind. The THz domain is largely dominated by thermal noise and material characteristics altered by individual and collective modes of molecular vibrations and rotations. Currently, analog-to-digital (ADC) conversion systems are seen as the bottleneck for THz applications. ADC systems available to date have to down-convert the THz frequency into GHz domain and then digitize the signal, adding to the complexity, weight, size, and power requirements of any such system. Using a series of electromagnetic input resonator that selects the band and polarization in series with a plasmon resonator-amplifier the detected electromagnetic signal is applied to a very low current FET. The detection is based on the nonlinear carrier perturbation process that makes the function of a down-converter. A fast ADC is digitizing the detected signal applying it to a set of fast memories. The detection chain repeated for various frequencies and grouped in a single multiband module - eye unit, is further integrated into the imager.

1. INTRODUCTION

The theoretic predictions showed that plasmonic, nano-heterostructures are able to selectively convert Terahertz (IR included) photons into electric detectable signal with the currently available technology of ultra low current or single electron field effect transistors operating at higher temperatures. The range of plasmonic hetero-structures made from an electromagnetic resonator (antenna) and a set of plasmon oscillators with the role of voltage amplifier and/or field propagators, perturbing a lower frequency signal by a nonlinear influence to the gate input of a FET. If the development of such system proves successful, then we have designs that we could apply to data quantification and processing, with the signal generated at the drain of the FET being further applied to a preamplifier stage and to an analog-to-digital converter.

Transitioning from the MHz to the THz domain of the electromagnetic radiation spectrum is just a scaling factor, but a scaling factor that makes a big difference from the materials availability point of view. The THz domain is the region where the manifestation of molecular characteristics (both individual and as a collective) becomes predominant and, while this is commonly perceived as the biggest impediment in the availability of materials for this frequency domain, it may also be the most attractive feature, if used appropriately. Seeing in THz means that one can see and resolve molecules, see their mass and temperature volume distribution, and more. From the airport security point of view it will be possible to see not only the passengers have dynamite in underwear but if they eat healthy food and all the constitutive molecules of the passenger are OK. Due to material characteristics in this domain, currently there are no near-future predictions for availability of materials able to detect large bands as in optics or low GHz domain. However, using current understanding of quantum dot confinement-based phenomena, some very specific resonators with high spectral resolution and sensitivity may be produced.

1.1 State-of-art of existing approaches

The current state of art is gradually attack the THz domain, similar to far IR by gradual approaches:

- Bolo-meter like devices ate the IR end where the photon energy is pretty high of few meV, requiring low or ultra low temperatures to eliminate the electronic noise as the thermal effect to be detected,
- Electronic like devices operating in GHz domain based on advanced junctions and nano-transistors able to operate up to few THz (even made in superconductor structures).
- Ultra-short pulsed laser interferometer devices with optical like imaging devices also operating in low THz domain also known as quantum-cascade lasers and mixers.
- Molecular resonant and tunable devices in MASER class operating mainly in narrow bands.

All the above devices requires large and sensitive cryogenic setups being compatible with static large space applications. The actual literature on this subject is so large with more than 500 patents applications and thousands of publications as I will refrain from giving any reference. None of them qualifies yet for the mobile, real time multispectral imaging and recognition on morphed surfaces or fly eye assemblies operating at normal temperatures and harsh environments.

2. DESIG AND DISCUSSION

The THz detection structure is composed of a chain of functional modules as: input resonator also called antenna, the THz photon induced signal pre-amplification, detection stage, amplifier, analog digital converter, memory buffer and data processing circuit also called imager.

2.1 The receiver input structure

At the core of the THz detection system is the basic structure of a double-gate MOSFET, in which one of the gates is replaced by a metal or semiconductor nanocluster (MNC/SNC), with a role of plasmon resonator. A diagram of the whole structure (including a wavelength-tuned antenna and a quantum dot field transmission chain) is presented below.

The type of material and size for the nanocluster will be selected during the Phase I. Also, while silicon is a good and obvious choice for building the FET given its ubiquity throughout the microelectronics industry, we will not discount alternatives such as gallium arsenide, or gallium nitride, silicon carbide (wide bandgap semiconductors suitable for harsher environments).

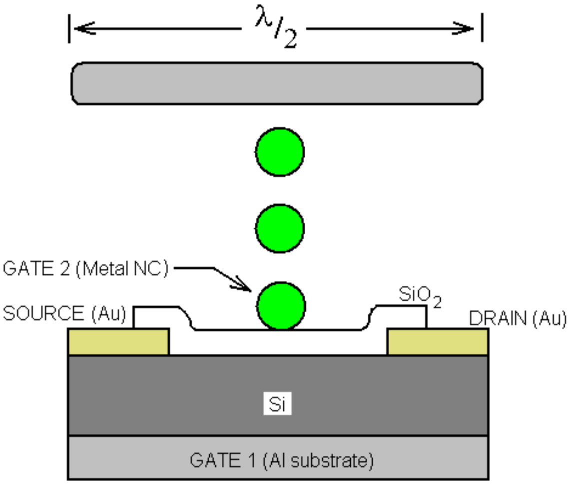

Fig. 1 – The input plasmon structure

In a basic design (without the antenna and the NC quantum dot chain), the NC placed on top of the oxide layer as a second gate to the FET is the primary THz resonator, sensing the electric component of the incoming electromagnetic field. The plasmon resonance of the nano-clusters will perturb the carrier density in the silicon channel of the MOSFET, thus modulating the electric signal passing through the device. However, the nanocluster's plasmon resonance will have only a narrow frequency width situated around the resonant frequency of the NC. The resonant frequency and its width are given by the dimensions and type of material that forms the nano-cluster preamplifier, as well as the refractive index of the surrounding medium (if the nano-cluster is capped by another material that would have to be quasi-transparent to that resonant frequency). We have more elaborate designs to widen the range of frequencies that would excite the NC, therefore increasing the frequency band acceptance of the whole device. Also, the nanocluster will be an omnidirectional signal receiver: if directionality is desired, then the addition of the frequency-tuned antenna and chain of nanoclusters for field propagation becomes a necessity. While Fig.1 show a line antenna, alternatives like a simple dipole or more complex YAGI-like setups could be envisioned. Other types of resonators with polarization or not may be considered, with the condition of being tuned on the nanocluster preamplifier arrays. Single or redundant detection was also be considered.

2.2 The detection electronics

The aim is to produce an elementary cell of a multi-band directive polarized array – which to be further used in creating vision structures like fly eye or by using appropriate optics to get multi-parameter imaging. The directive multi-band vision is an important element in detecting imaged object material's properties.

The structure has the following parts:

- Directive polarized resonator – also called antenna – which may be similar to a yagi structure (see figure 1). The resonator has a reflector, vibrator used to select the polarized photons coming from the right direction. A resonant structure used to capture the photon energy and transform in local oscillation modes, with the capability of frequency selection and resonant amplification.
- A voltage converter-amplifier, made by passive micro-nano structure elements which takes the resonator voltage and amplifies it driving to a field effect differential active element, where the voltage is transmitted as gate polarization, so that a single photon to become possible to be detected.

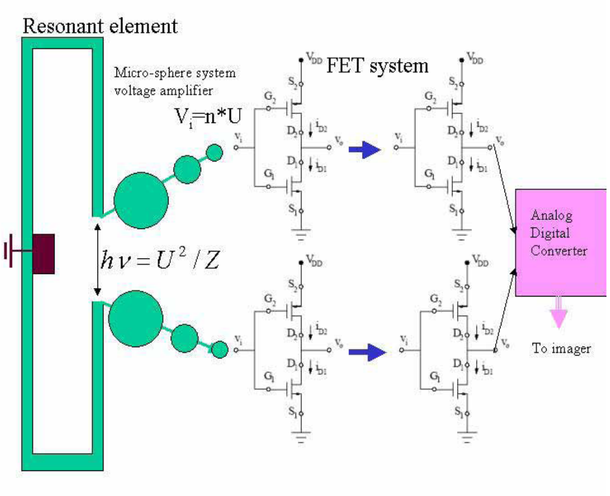

Fig. 2 The detection chain

- The active amplifier made from a FET structure, running an alternative carrier like frequency in GHz domain, in a differential mode. When the THz voltage is attacking the gate, this is transmitted as a perturbation in the driving frequency, and the differential signal is collected and amplified.
- A signal collection and amplification system that takes the signal from each sensor and transmits it to a data acquisition device that is taking the signals in event mode or in amplitude mode.
- A computer device that is interpreting the acquired data and delivered for further utilization like imaging, detection, material identification

2.3 The plasmon resonator – converter

The single photon energy in the domain of 1mm to 1 μm wavelength, corresponds to wave number range 10-10,000, with energy in the domain of 1.2 meV to 1.2 eV for 1 micron IR. This energy applied for a reasonable time supposing the photon-associated wave has a finite length similar to that measured in optical experiments [1] may drive to a voltage in the picoVolts to nano-Volts range.

Stockman et al. proposes one of the most efficient passive "amplifiers" [2, 3, 4] design based on a chain of spheres. The dimensions of our resonators are in the sub-milimetric domain down to 1 μm and the voltage collector is less than ½ μV. The minimal sequence of "nanolens" [2] drives for a minimal final dimension for the MOS-FET gate in the range of 30 nm up to 10 μm. They proved that the electric potential in the small sphere region / our FET-Gate φ as function of the potential in resonator φ_o and

$$s(\omega) = {}^{1}\!/_{1-\varepsilon(\omega)} \tag{1}$$

being the spectral parameter [5] and,

$$\varphi_0 = -zE_0 \tag{2}$$

$$\varphi(r) = \varphi_0(r) - \int \varphi_0(r') \frac{\partial^2}{\partial r'^2} \times \\ \times \sum_{\alpha} \Phi_{\alpha}(r) \Phi^*_{\alpha}(r') \frac{s_{\alpha}}{s(\omega) - s(\alpha)} d^3 r' \tag{3}$$

Using numerical computations values for voltage gain of about 10^3 or greater were obtained [2].

The combination of low plasmon impedance and shape factor, with high dielectric media impedance makes the efficiency of the plasmon voltage converter very high, while the resonance condition narrows the band-pass, making the whole system to be frequency and polarization selective [6]. The electronic detection system relies on nonlinear carrier perturbation method.

The detection transistors are symmetrically crossed by a high carrier frequency that is perturbed by the gate electric parameter variation making the differential amplifier detect a signal out of electronic noise for each photon up to the high level of signal due to thermal emission. There are various combinations possible to enhance the detection resolution and to extract the useful signal from the thermal noise. The final amplifier stage transfers the signal to a time-of-flow-ultra fast analog digital converter that accesses a special fast multi access memory bench.

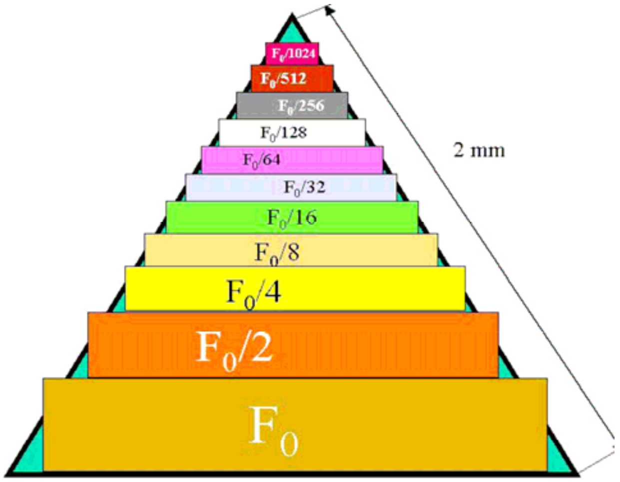

Fig. 3 – Compact multi-band antenna module

2.4 Multiple band detection

This structure may be repeated to detect difference frequency bands, using in correlation the directivity and phase selectivity properties of the resonators with the amplitude signal detection to produce a multi-band detection system, creating a pseudo-chromaticity in the T-ray field. Fig. 3 shows one input resonators grouping alternative, suitable for polarized "antenna". It was also analyzed the possibility of printing the resonator structure on had dielectric materials as diamond, sapphire, silicon carbide to create a hardened structure able to be used in harsh environments or fast moving objects. Any combination of various input resonator is possible as creating detection modulus with triangular, square, hexagonal, etc. cross-sections able to be assembled in various structures.

Because the resonators may be shaped in various aspect ratios there is possible to compact the various waveband centered resonators into a single detection module, called multi-band antenna, as Fir. 3 shows for a Yagi like rectangular structure.

To create an imaging device several procedures have been analyzed as:

- use a optical like lenses to produce a image in a narrow single band on a multi-detector plate
- a fly eye similar configuration made by a multitude of directional detectors
- a computed image generated by a morph detector array similar to the SAR

The T-ray chromatic vision is an in-depth vision selective to molecular parameters having large applications from medical, to scientific and military.

2.5 Data processing and integration

The resonator preamplifier structure has to be followed immediately by the detection module. Due to high frequency the carrier may have in GHz domain, the ADC have to be placed immediately near the module. It is recommended as an integrator circuit with sample-hold to be used, to generate the detection time-frame stability in the input of the ADC. The ADC no dead time is required, and a specific multiple-access buffer memory at high speed is required. When the working frequency is in GHz domain suitable to visualize molecular chemical kinetics the data storage and processing is a challenge to the actual technology. There were analized various data transfer configurations to memory banks due to the fact that the usual acquisition and transfer speed is in the range of several hundreds Giga-bauds. In practice not all molecular processes are evolving in ns level and there are several solutions for the detection electronics:

- to deliver a longer analogical integrator in front the ADC or digital integrator immediately after the ADC with the desired optimal frame rate
- to leave the electronics fast but to process the images by time-line integration.

The first alternative drives to a cheaper solution but more sensitive to S/N ratio, while the second one drives to a more versatile imager but more expensive also. Depending on application the best performance/cost technical solution may be selected. The molecular vision concept comes from the fact that most of the molecular combinations have their vibration mode emission in THz bands. Using a multi-band detection the possibility of performing advanced signature detection by fusion of the various channels with the specific weight is driving to molecular bounds recognition. More the multi-band correction may also determine the average temperatures in the molecule's elemental volume by detecting the temperature driven bands shift.

Special developed software and calibrations are needed to improve the detection accuracy. Knowing the detection vectors and the angular distribution of the input antenna array makes possible the three-dimensional imaging.

2.6 Applications briefing

The THZ detection is providing the following information after appropriate calibration:

- Detection direction and angular distribution of sensitivity
- Polarization,
- Central frequency and bandwidth
- Time of detection, and synchronization
- Amplitude

for each detector chain, inside a multi-band module, and for each module in the form of a 8-12 bit signal for each detection point.

Using this information into a specially programmed array, similarly to neural network several classes of visualizations can be made almost simultaneously:

- Complex 3D-time space information
- Detection of fast transitory evolutions if over the S/N fluctuations or some correlation exists
- Chemical compounds identification and their trend and kinetic rates (reaction, diffusion, etc.)
- Temperature fields as voxel averages per each type of molecule
- Cuasi-static image at the TV broadcasting rate, and more.

With features, and the fact that these rays have various penetration in depth in various materials as clothing up to 0.2 m, walls, soil, etc. the applications are in military domain, security, medicine in metabolism and organs remote imaging, environment, industry, preventive health, chemistry, reverse engineering, space applications and more.

3. CONCLUSIONS

The actual researches in the THz domain showed the possibility of obtaining a multi-band "far-IR" (sub-milimetric EM wave) imager.

The QED calculations play an important role, due to complex interactions between the lattice and photon quanta.

Low temperature electronics – near single-electron-transistor have to be used. The build-up of the multi-band THz sensor opens the way to a wide range of THz imaging applications.

Clustering and grouping the sensors under computer image control offers the possibility of having compact surface detection of the surrounding space in multi-band domain from GHz to THz with a great importance to wide range of application.

The application domain is very large, from military, security to medical and research, in space or terrestrial.

4. ACKNOWLEDGEMENTS

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