Controllable metamaterials for THz applications

I.B. Vendik[1], O.G. Vendik[1], M.A. Odit[1], D.V. Kholodnyak[1], S.P. Zubko[1], M.F. Sitnikova[1], P.A. Turalchuk[1], K.N. Zemlyakov[1], D.S. Kozlov[1], I.V. Munina[1], V.M. Turgaliev[1], Y. Park[2], J. E. Kihm[2], and C.-W. Lee[2]

[1] Microwave Microelectronics Laboratory, Department of Microelectronics and Radio Engineering, St. Petersburg Electrotechnical University "LETI"
5, Prof. Popov Str., 197376, St. Petersburg, Russia
Fax: + 7812 3460867; email: ibvendik@rambler.ru
[2] Samsung Advanced Institute of Technology
Yongin-si, 446-712, Suwon, Korea Fax: + 82-31-280-9349 ; email: chang-won.lee@samsung.com

Abstract

This paper presents a review of controllable metamaterials (MTM) for THz applications. More than 150 original papers have been analyzed. The following MTMs are under discussion: SRR based MTM, all-dielectric MTM, ferroelectric based MTM, ferromagnetic based MTM, liquid crystal based MTM, MTM for the wave polarization control, and layered metal-dielectric structures. Different methods of control have been analyzed: by electric field, by magnetic field, optical control, and by temperature. In conclusion, assessment of the MTMs considered is given.

1. Introduction

Terahertz (THz) science and technology attracts attention of scientists during last few decades. Devices for modulating and detecting THz radiation are considered being realistic for commercial purposes. A great interest of new applications in THz spectrum is provoked by a possibility of THz imaging and sensing. Among many other applications THz can be used for medical scanning, security screening, quality control, atmospheric investigation, and space research. However, it is still a big challenge to make it possible to manipulate THz radiation at a desired way due to the lack of appropriate ultra-high frequency electronic devices. Artificial structured materials, known as electromagnetic metamaterials (MTM), play an increasingly important role in a design of functional THz devices.
Manufacturing MTM for THz spectrum is a challenging task. The size of the unit cell of the MTM structure for THz region is to be scaled to micrometers or even hundreds of nanometers in comparison with millimeters for microwave region. More efforts on new designs and fabrication methods must be undertaken in order to use MTMs for applications with controlled performance. The MTMs are expected to be a base of THz controllable devices, which cannot be realized using conventional materials.
This paper presents a review of methods of design of controllable MTMs for THz applications. More than 150 original papers have been analyzed with respect to their approaches to controllability. Different types of MTMs and methods of control of electromagnetic properties of the THz MTM will be discussed.

2. Metamaterials for THz applications

SRR based metamaterials. Most implementations of MTMs are based on a combination of split-ring resonator (SRR) structures to obtain a magnetic response and wire structures to obtain an electric response. The SRR structure without wires displays magnetic and electric responses under normal incidence radiation with the magnetic field lying completely in the SRR plane and

ISBN 978-952-67611-0-7

electric field perpendicular to the SRR gap. This allows the electric field to drive the inductive-capacitive resonance. The control of transmission is provided by using MEMS-like SRR structures. The effective resonance results in a frequency dependent transmission, where, at resonant frequency, a strongly enhanced electric field is concentrated in the gap of the SRR; the resonance disappears when the cantilever bends down to touch the SRR and shorts the gap.

A different way to produce reconfigurable MTM is integrating semiconductors into MTM designs. The multi-mode electric-field-coupled (ELC) resonator contains a set of gaps, which can be shunted by optical illumination. Depending on the distribution of open and closed gaps in the ELC resonator, the transmission (rejection) can be provided at different frequencies. The attenuator can be designed on the SRR based MTM by changing the conductivity of semiconductor in the gaps under optical control.

SRR based structure immersed in controllable medium (ferroelectric, ferromagnetic, liquid crystal etc.) is a good candidate for a design of tunable MTM in THz frequency range.

THz metamaterials based on resonant dielectric inclusions. The all-dielectric metamaterials are based on magnetic or electric resonance (Mie resonances) in dielectric inclusions of different forms: sphere, cylinder, cube, rod etc. A regular array of the resonant inclusions exhibits a single-negative or double-negative response in THz range by implementing resonators of suitable dimensions and the dielectric material with a rather high dielectric permittivity. Using ceramic materials whose dielectric permittivity is sensitive to temperature variations, one can control the transmission spectrum of the all-dielectric MTM in THz frequency range.

Tunable THz metamaterials based on ferroelectrics. The field-induced tunability of the dielectric properties of $SrTiO_3$ (STO) thin films was demonstrated in the THz frequency range at room temperature. At 100 kV/cm, the permittivity decreases by 11% and remarkably changes the frequency depending response. The Mie resonance in the nano-rod structure of STO was used to tune the transmission spectrum by the temperature control. This method of control is effective, but slow. Using electrically con-trollable thin ferroelectric layers is promising for a design of a very fast tunable MTM.

Tunable THz metamaterials based on ferromagnetics**.** Introducing ferromagnetic rods into the SRR/wire array and applying *dc* magnetic field is used for tuning transmission properties of the MTM. Magnetic and dielectric resonances in the sub-THz frequency range (0.1 THz) are observed in pure and Al-substituted hexagonal barium ferrite**.** Sub-THz resonances in hexaferrites have been used to design ferrite based devices: resonators, isolators, and phase shifters. MTM based on ferrite-piezoelectric and ferrite-ferroelectric (FE) layers consisting of piezoelectric (PE) and piezomagnetic (PM) oxide material layers is promising. Complex FE, PE, and PM oxide materials are known for their extraordinary responses to optical and THz frequencies. A hexaferrite-piezoelectric bilayer composed of single-crystal hexagonal ferrite $BaAl_2Fe_{10}O_{19}$ and PZT can be used for tunable devices with control of the frequency both by the magnetic field and by the electric field. Such structures can be used for dual electric and magnetic field tunable resonators, filters, and phase shifters.

THz metamaterials based on liquid crystals**.** Liquid crystals (LC) have anisotropic properties that are sensitive to external fields. Their fluid nature allows easy incorporation into various geometries and nanometer scale pore sizes. These advantages of LC and their sensibility to external fields can be used for designing THz tunable materials and devices. The structure of 3-D MTM formed by randomly dispersing spherical core-shell molecules in a LC host demonstrated that when the relative permittivity of the LC is changed, the MTM can be tuned to have a negative index, a zero index, or a positive refraction index for the same THz operating frequency. The LC based MTM are controlled by an electric field, a magnetic field or temperature.

THz Wave Polarization Control Devices**.** The polarization sensitive THz MTM devices show directionally asymmetric trans-mission of circularly polarized waves. The total transmission level of circularly polarized waves through a planar chiral MTM pattern depends on both the wave handedness and the propagation direction. The MTM structures are based on pairs of SRRs of orthogonal orientation that are joined together forming a two-dimensional chiral pattern. Polarization sensitive MTM unit was obtained from the SRR by breaking the circular symmetry: replacing the inner split ring with a split ellipse. When the incident polarization is horizontal (parallel to the major axis of the ellipse), there are two minima at two different frequencies. As the angle increases, these minima gradually decrease while other resonances appear and gradually become prominent. When the incident polarization is vertical (perpendicular to the major axis of the ellipse), there are again only two minima at other two frequencies in THz range. The phase control could be applied for building a quarter-wave plate or polarizing THz beam splitter using the anisotropic metamaterial. The single anisotropic metamaterial layer acts like a wave plate imparting an equal amplitude change and a different phase shift to the horizontal and vertical electric field.

Layered metal-dielectric structures of THz metamaterials. The metal-dielectric-metal (MDM) structure consisting of periodic square-loop slotted metallic arrays on both sides of a thin dielectric substrate exhibits a broad band-pass transmission response. The electromagnetic response of such a MDM structure is influenced by the dielectric permittivity and the thickness of the substrate. The slotted metal-dielectric structure with tunable permittivity or permeability demonstrates an effect of tuning the center frequency f_0 and the frequency band Δf. If the permittivity decreases, f_0 is blueshifted and Δf is broadened. In case of using ferroelectrics, the tunable permittivity of the ferroelectric layers controlled by the voltage applied to different metallic layers makes it possible to tune the resonance frequency and the bandwidth of a THz device based on MDM MTM.

3. Conclusion

We have discussed controllable MTMs for THz applications in terms of their physical designs and possible realization. There is a wide area of potentially useful applications of tunable and reconfigurable MTMs in the THz frequency range. Using tunable materials (ferroelectrics, ferromagnetics, liquid crystals) as constituents of the structure for a design of controllable MTMs is promising.

A variety of different THz metamaterial structures has been analyzed. These structures can operate as band-pass and band-stop or low-pass filters, polarizators, attenuators and switches. The structures are classified as metamaterials and described as artificial media with single or double negative properties. Negative permeability and/or negative permittivity were demonstrated by existence of resonant stop-bands and pass-bands. Electromagnetic field analysis confirmed the backward way propagation in the DNG structures considered. Methods of control of operational bandwidth of MTM structures and range of tunability have been estimated.

Different methods of metamaterials structure control have been considered. The most convenient is optical control affecting semiconductor conductivity in the metamaterial structure. It is the fastest way of control and can be used in THz switches.

The MEMS technology opens new perspectives for tunability of the metamaterial structures for THz. It allows changing artificial metamaterial parameters by changing applied voltage.

Among various natural materials ferroelectrics should be highlighted as a promising candidate for active THz metamaterial structures. The THz technique is well known to be used to study ferroelectric materials because of their remarkable response at THz frequencies. At the same time these materials can be effectively used to control THz radiation. The properties of ferroelectrics can be tuned by temperature and voltage. Different kinds of ferroelectric materials with variety of different composition can be prepared in order to get desired permittivity and different loss level for different ranges of frequencies and temperatures.

Among all the structure considered the most promising designs are SRR with semiconductor inclusions (optical control) or MEMS-based structures (voltage control), dielectric-wire-medium structure with temperature control and MEMS-based resonating patch arrays.