Modelling of Electronically–Controlled Filters of Microwave (SHF), SubTHz and THz–Bands Based on Graphene Meta–Surfaces

L V Cherchesova¹, P N Bashly² and D A Bezuglov²

¹ Don State Technical University, Gagarin Square 1, Rostov-on-Don 344000, Russia
² Russian customs academy, Budennovsky 20, Rostov-on-Don 344002, Russia

E-mail: bezuglovda@mail.ru

Abstract. Development of generating and receiving radiation methods and means by microwave, sub–Hz and THz ranges is connected with the creation of new high–speed elements of radioelectronics based on new nanomaterials. These includes graphene and nanotubes, in order to develop highly efficient tunable nanophotonics devices for signal processing using new principles, materials and structures. The creation of transmission lines, filters, parametric generators and amplifiers based on multilayer graphene structures is very perspective. However, for today, the physical phenomena and effects in graphene nanostructures are investigated poorly; there are no engineering methods of devices calculation, which is the main difficulty in the way of radioelectronic devices creating of new generation with new element base on the ground of graphene. For investigation of new nanoscale properties and functional possibilities of devices based on nanostructured materials and components – microresonators, transmission lines, antennas, etc. – in the microwave, sub–Hz and THz ranges, a unified approach to their mathematical modelling is required. To overcome the limitations associated with the calculation methods and design, the authors are grounding on the ideas of computational electrodynamics, successfully implemented in computer– aided modelling and design systems in the SHF technique.

1. Introduction

High mobility of charge carriers in graphene makes it the promising and perspective material for using in various applications, as one among the future bases for nanoelectronics and possible replacement of silicon in integrated circuits; it contributes to the creation of radioelectronic devices and arrangements of microwave, sub–Hz and THz–bands. Progress in the production and formation of figured graphene presents great opportunities for the creation of tunable microwave, sub–THz, THz metamaterials and integrated plasmonic devices with potential applications in the filters and polarizers [1].

Using of figure graphene represents enough interesting for overcoming the limitations of existing technologies, in terms of operating frequencies, complexity of electric displacement due to the known effect of graphene controllability of by electric field, as well as integration and nanominiaturization [2].

New directions, perspectives and applications appear in the field of graphene–based metamaterials and their 2D versions, metasurfaces and ultra–thin structures. Graphene–based meta–materials with artificial structure of the resonance elementary cell make it possible to combine functions, such as in
microwave devices with control of absorption frequency, modulation, polarization and reflection / absorption at switching (Figure 1) [3].

Figure 1. Layers of graphene on silicon substrate (image from electron microscope with magnification of 5000 times).

Research promotion of in the field of microwave, sub–Hz and THz frequencies was carried out both from the side of range millimeter waves and from the side infrared radiation spectrum. In the course of mastering, methodological approaches and technical solutions peculiar to both microwave technology and optics were introduced into research process of the THz range. As a result, both the lower and upper bounds of sub–THz range turned out to be "blurred", and the methods of research and practical development were different for low – frequencies and high – frequencies areas of the THz band. These ranges are the area of electronics and photonics convergence, significantly different as the theoretical base, and the technique of generation, implementation of reception and processing of electromagnetic waves. Development and implementation of microwave, sub–Hz and THz systems for various purposes are directly depending on success in the field of modern electronics and photonics [4].

The obvious advantages of THz range radioelectronics: the absence of ionizing influence effects, the large information capacity, the ability to penetrate through non–transparent objects, the possibility of high directional radiation and some others – have determined the fast development of THz technology in the whole world. These advantages determine the attractiveness of practical application of THz waves for the creation and construction of high–speed communication lines; high–precision radiolocation stations (radars), capable of operating in the complex electromagnetic environment; systems of image reception with very high resolution; arrangements of chemical substances distance identification and other military and civilian equipment [5].

Modern telecommunication systems are intended for the organization of digital information networks for data, voice, and video transmission. The most prospective are the fiber –optical systems of information transmission, which means that the increase in the efficiency of fiber–optical systems of information transfer is largely determined by the general trends in the development of optical technologies. This is due to the constant increasing of the amount of information transmission via telecommunication systems. Therefore, the increase in the transmission capacity and the speed of information transmission along the fiber–optical communication lines are the main tasks and problems to improving the efficiency of information transmission systems [6].

The speed and transmission capacity of fiber–optical information transmission systems are determined by the capabilities of optical waveguides, the operation speed of the element base of radioelectronics and optoelectronics. The improvement of the element base depends on the level of development of the production technology and on the successes in the creation of new materials and substances.

The operation speed of the radioelectronics element base is determined by the time of electron flight, consequently, its speed and the length of the gate of the transistor. Therefore, the maximal operating frequency of information processing and transmission devices depends on the electronic characteristics of materials and substances and on the geometric dimensions of the microelements. With decreasing in the geometric dimensions, the precision of the element base fabrication should be increased. However, there are technological limits related to parameter spread, power consumption
and heat generation, as well as physical limits of size (dimension) decreasing. To further improving of the transmission velocity and operation speed, the transition to low–dimensional structures is needed.

Future technologies will require from photonics the devices creating with high degree of integration and energy efficiency, much more advanced the volumetric optical components in the silicon photonics. Such integration can be achieved by combining signal processing functions and waveguide properties at the material level, creating a new concept of meta–structures and meta–devices. It can be assumed that strength (durable) and reliable meta–devices will allow to photonics competing with electronics not only in telecommunication systems, but also at the level of consumer products, such as mobile phones, TVs and cars. The main problems in achieving this prospect are the development of economically efficient production and technologies for meta–devices integration [7].

The aim of the research is to create high–speed elements grounded on graphene in order to develop highly efficient tunable nanophotonic devices for signal processing using new principles, new materials, substances and structures.

The research tasks consist in mathematical modelling of energetic–controlled filters of microwave, sub–THz and THz ranges based on multilayer structures of "graphene – dielectric".

Scientific novelty of research consists in establishing the fact that the studied periodic multilayer microstructures of the “graphene–dielectric” type can be used to create wideband filters of microwave, sub–THz and THz ranges of the planar design, controlled by electric field and fast tunable with small changes in the Fermi’s energy level of graphene.

2. Graphene–based filters and their characteristics
The structure low–frequencies filter of nth order based on graphene consists of graphene band and several polysilicon gate elemental area located below it, as shown in the figure 2.

![Figure 2. Low – frequencies filter of nth order of microwave range based on graphene [8].](image)

The band promotes the propagation of localized transverse magnetic plasmons; the resistance can dynamically change along the entire length of the structure by applying of different bias voltages (displacement) to the gates. If all the gates are displaced equally, the structure behaves as a simple plasmonic transmission line. When different bias voltages (displacement) are applied to the gate elemental areas, the resistance increases due to the field effect in graphene. This conception is used to the implementation of lower frequencies filters with step change in resistance, which consist of cascade of transmission lines with high and low wave resistance. The filters cut frequency can be dynamically tuned (adjusted) by simultaneously changing of the constant displacement field applied to the gates.

S–parameters of the filter scattering matrix are shown in the figure 3. The filter is intended to obtaining of cut frequency in 2.3 THz. The results were obtained using the procedure of ideal synthesis (Figure 3, a). The restructuring of the filter is occured by changing of the constant (bias) field of displacement on the various gate elemental areas (Figure 3, b).
Figure 3. S – parameters of filter scattering matrix in dependence on frequency: W = 150 nm, dielectric constant of substrate $\varepsilon_r = 1.8$ [9].

Rejective (band–stop) plasmonic filters of Sub–THz and THz ranges made using steaks from five layers of coated micro – disks of graphene with high filling coefficient [10].

On the figure 4, a, there is shown the spectrum of THz wave transmission through two grating (lattices) of disks with the same diameter $d$ (4.4 mm), but with different periods of grating (lattices 4.8 and 9 mm), made of graphene monolayer.

The single–layer lattice of graphene disks has very high maximal absorption. It also features enough low plasmonic resonant frequency. This is consequence of Coulomb’s interactions between disks within the same layer.

The resonance weakens when a smaller grating (lattice) period is used, which is due to interaction of graphene disks in the same layer. In the figure 4, b, is shown the spectra of THz waves passing through filters with different diameters $d$ of disks. The grating (lattice) periods $a$ are greater than the diameters $d$ of the disks by 400 nm. At using of such gratings (lattices) of micro–disks, the maximum of relative absorption of 85% is achieved, which makes it possible to create the rejective filter with attenuation (dissipation) coefficient of 8.2 dB.

The maximum attenuation can be achieved by changing the diameters $d$ of the micro – disks, as it is shown the in figure 4.

The resonance frequency is modified by changing the diameters of these micro–disks [11].

Figure 4. Transparent filters of microwave range [11].

In ultra–narrow graphene tapes, only the surface wave propagates, which can simplify the electromagnetic coupling (connection) between objects. This feature is used for the production of filter construction (design) of two graphene nano– tapes, related with graphene ring cavity (annular) resonator [12].

In the figure 5, the structure of planar band–pass filter based on graphene monolayer with obstructing (blocking) device, in which the different values of the bias voltage (displacement) in the different zones are used, for creation of inhomogeneous conductivity is demonstrated.
Figure 5. Structure of planar band–pass filter consisting of two graphene waveguides connected by graphene ring resonator of graphene monolayer, where $L$ – length of graphene waveguide; $W$ – width of graphene ring; $R$ – external radius [13].

Plasmon filters based on single– and double– layer doped graphene metasurfaces in microwave, sub–THz and THz ranges were investigated in the work [13] using the finite differences in the temporal domain method (FDTDM).

The cell structure of meta–surface element consists of two parallel symmetrical and asymmetrical structures, fulfilled from the graphene nano–tape.

At the first step the meta–surface is considered, which cell consists of two parallel symmetric graphene nano–tapes (figure 6, a). The geometry of the meta–surface cell of element, which is located in the center of the quartz substrate ($n = 1.5$), is schematically depicted in figure 6, b. Normal incident THz radiation, polarized perpendicularly to the nano–tapes is used for exciting of surface plasmons regime.

Figure 6. Plasmonic rejective filter based on graphene meta–surface; structure of elementary cell of meta–surface, consisting of two symmetric nano–tapes of graphene, located parallelly with geometric dimensions: $a = b = 800 \text{ nm}$, $c=550 \text{ nm}$, $d=125 \text{ nm}$, $e=120 \text{ nm}$, $h=200 \text{ nm}$; the frequency dependencies of transmission coefficient through the filters based on single– and double–layer structures of symmetric nano–tapes of graphene for different values of the chemical potential. Curves:
1) $\mu_c = 0.6 \text{ eV}$; 2) $\mu_c = 0.56 \text{ eV}$; 3) $\mu_c = 0.52 \text{ eV}$; 4) $\mu_c = 0.48 \text{ eV}$ [14].

Surface plasmons of TM–waves (Transverse Magnetic waves) can propagate perpendicularly to the direction of the nano–tapes with low losses, and plasmonic modes are forming the standing (stationary) wave in the nano–tapes. Periodic boundary conditions in the $x$ and $y$ directions are used for modelling of the experimental investigated sample.

On the figure 6, c, below, the results of modelling – the calculated frequency dependences of the transmission coefficient of the plane wave through single – layer and two – layer structures of symmetric graphene nano – tapes, respectively, for different values of the chemical potential $\mu_c$ (Fermi energy) are demonstrated. The resonance frequency of the filter can be controlled. Almost ideal perfect filtering ($T_{min}$) can be achieved in the tuning range.
In comparison with a single–layer meta–surface, in the structures with double graphene layer it is possible to increase additionally the resonance frequency in the direction of higher frequency area of the THz spectrum.

On the next step the meta–surface is considered, which cell consists of two parallel asymmetrical nano–tapes of graphene (figure 7). The geometry of the meta–surface element cell is schematically shown in figure 7, a; geometric dimensions: g=450 nm, other parameters are the same as in figure 6, b.

On the Figure 7, b, c, there are demonstrated the results of modelling – calculated frequency dependences of transmission coefficient of plane wave through single–layer and two – layer structures from the asymmetric nano – tapes of graphene, respectively, for different values of the chemical potential (for the case of incident of SubTHz / THz radiation polarized along the graphene sheets). The results show that the resonance frequency clearly changes in the direction of higher frequencies with an increase in the chemical potential $\mu_c$ (Fermi energy).

Comparing two frequency dependences of transmission coefficient in the figure 7, c, it can be discovered that there are two deep minima in the filter characteristics for two–layer asymmetric structure. Polarization of electrical field of incident THz radiation has influence on its transmission through the long and short graphene nano – tapes.

**Figure 7.** The cell structure as element of meta–surface composed of asymmetric graphene nano–tapes of parallel orientation. Frequency dependence of coefficient of transmission (passing) through the filters based on single– and double–layer structures of asymmetric graphene nano–tapes for different values of chemical potential. Curves: 1) $\mu_c = 0.6$ eV; 2) $\mu_c = 0.56$ eV; 3) $\mu_c = 0.52$ eV; 4) $\mu_c = 0.48$ eV [14].

Results of modelling show that significant displacements of resonance frequency can be achieved with small changes in the concentration of graphene nano – tapes doping.

Meta–surfaces with symmetrical single – layer or asymmetrical double–layer graphene can be used as highly sensitive refractive sensors with sensitivity up to 5100 nm and double–circuit switches. These prospects pave the way for the creation of superfast plasmonic devices based on graphene in the microwave, sub–THz and THz ranges.

### 3. Electronically controlled filters of thz range based on graphene metasurfaces

In [15], graphene metasurfaces for transmission of radiation induced by plasmons in THz range, whose cell consists of the structure based on graphene ring and graphene nano–tape, were investigated. Both graphene rings and graphene nano – tapes create radiation transmission regimes (modes) – transparency spectral windows induced by electric dipole resonances.

Weak hybridization between the two elements leads to appearance of new window of spectral transparency induced by plasmons, which can be controlled by changing the geometric dimensions of
the graphene–based meta–surface cell structure. The resonance frequency of the transparency spectral window can be dynamically tuned in a wide range of THz frequencies, changing the chemical potential (Fermi energy) of graphene by applying an external electric field (electrostatic sampling, gating) instead of re–producing of the structures [16].

Figure 8 shows the structures of graphene–based meta–surface cells to demonstrate the phenomena of radiation induced by plasmons. The basic elemental cell of the meta–surface consists of graphene ring and a graphene nano–tape. The inner and outer radiuses of graphene ring are $r_1 = 2 \ \mu m$ and $r_1 = 3.2 \ \mu m$. Length on the nano–tape is $L = 9 \ \mu m$ and width $W = 0.7 \ \mu m$. The dielectric substrate is photopolymer with relative dielectric permeability $\varepsilon = 2.4$ and thickness $h = 0.5 \mu m$. The structure is located along the $x$ and $y$ directions with period $p = 10 \mu m$. The incident wave is perpendicular to the $x – y$ plane with polarization $E_x$.

![Figure 8. Meta–surfaces cells of different configurations: graphene ring operating in the regime of window spectral transparency for the radiation, induced by plasmons [16].](image)

To demonstrate the effect of radiation induced by plasmons, the frequency dependences of the transmission coefficient of passing through the filters based on graphene meta–surface with the elementary cell were calculated. This is composite structure based on graphene ring and graphene nano–tape (curve 3 in figure 9); single graphene nano–tape (curve 2); and single graphene ring (curve 1); for the value of the chemical potential (Fermi energy) $\mu_c = 0.5 \ eV$.

![Figure 9. Frequency dependence of transmission coefficient through the filters based on graphene meta–surfaces for various configurations of meta–surface elements. Curves: 1) graphene ring; 2) graphene nano–tape, 3) structure based on graphene ring and graphene nano–tape [16].](image)

From figure 9 it is obviously, that when at association of graphene rings and graphene nano–tape in the composite structure, oriented along the direction of the electrical field, the window of spectral transparency for THz radiation, induced by plasmons, with transmission coefficient more than 95% is observed at frequencies $f_1 = 1.68 \ THz$ and $f_2 = 2.14 \ THz$.

To demonstrate the physical mechanism of plasmon–induced radiation effect, on the figure 10 is shown the calculated distribution of electric field for three resonant frequencies of the filter $f_1 = 1.68THz$, $f_2 = 1.86 \ THz$, $f_3 = 2.14 \ THz$, which correspond to minimum of transmission coefficient (figure 9).

In figure 10, a, at the first resonance at the frequency $f_1 = 1.68THz$, it is seen that the nano–tape is excited strongly by the incident electric field, and the ring is excited weakly.
Figure 10. Electric field distribution for frequencies [17]: a) \( f_1 = 1.68\text{THz} \) – first minimum of transmission coefficient; b) \( f_2 = 1.86\text{THz} \) – second minimum of transmission coefficient; c) \( f_2 = 2.14\text{THz} \) – window of spectral transparency of radiation.

At the second resonance at the frequency \( f_2 = 2.14\text{THz} \) (figure 10, b), the optical response of the ring and nano–tape is mainly concentrated on the ring, which behaves as optical antenna and oscillates with external electric field. Both resonance creates window of spectral transparency for THz radiation induced by electric dipole oscillations. Figure 10, b is shown the electric field at the third resonance frequency \( f_3 = 1.86\text{THz} \). Quadrupole oscillation appears on the ring and nano–tape, and the phase resonance emerge in two component composite parts: graphene ring and nano–tape ones.

Influence of geometric dimensions on the response of THz radiation, induced by plasmons, was numerically investigated. Result is the fact, that with increasing length \( L \) of nano–tape, the first resonance \( f_1 = 1.68\text{THz} \) is rapidly changing towards lower THz frequencies [18].

The second resonance \( f_2 = 2.14\text{THz} \) does not change; thus, the interval between two resonances and maxima transmission coefficient increases. The dependence of resonance frequency on graphene nano–tape length \( L \) is plotted. As the length \( L \) increasing, the frequency displacement of second resonance keeps invariance and the frequency \( f_1 \) of the first resonance changes very quickly. Similarly, at increasing the width \( W \) of the graphene nano–tape the first resonance is displaced towards higher THz frequencies, while the second resonance keeps invariance, and windows of spectral transparency for THz radiation, induced by plasmons, is narrowed sharply.

Figure 11. Frequency dependencies of transmission coefficient through the filter at different value of the chemical potential of graphene. Curves: 1) \( \mu_c = 0.3\text{eV} \); 2) \( \mu_c = 0.5\text{eV} \); 3) \( \mu_c = 0.7\text{eV} \).

The surface conductivity of graphene can be changed by controlling its chemical potential (Fermi energy) \( \mu_c \). Control can be realized by changing the chemical doping (alloying) or electrostatic gating (sampling). Dynamic control of the windows spectral transparency of the meta–surface is realized without geometry reconstruction or introduction of other controlled materials by changing the chemical potential.

On figure 11, the frequency dependences of transmission coefficient at different values of graphene \( \mu_c \) are shown. The window of spectral transparency can be tuned effortlessly in a wide range of frequencies by small changing of the chemical potential \( \mu_c \) (Fermi energy). When \( \mu_c \) is increasing from 0.3 to 0.7 eV, the resonance frequencies rise too, from 1.47 to 2.25 THz, thanks to what the window of spectral transparency rebuilds completely [19].
4. Electrodynamic calculation of THz range filters characteristics based on multilayer structure of type “graphene – dielectric”

Principles of construction of THz–band filters, controlled by the electric field, are investigated, and the electrodynamic calculation of their characteristics is carried out by the FAB (Autonomous Floquet Blocks) method [20].

The calculation model of sub–THz / THz range planar filter based on the periodic multi–layer structure of type “graphene–dielectric” is demonstrated in the figure 12.

Using the computational algorithm, based on FAB method, the electrodynamic calculation of elements scattering matrix of the filters of sub–THz / THz range, based on periodic multi–layer structures “graphene–dielectric” type in THz range.

Figure 12. Calculation model of the planar filter THz range based on periodic multi–layer structure of type “graphene–dielectric”.

On the figure 13 are shown the calculated frequency characteristics – dependences of the element |S21| scattering matrix – transmission coefficient of TEM–wave (Transverse Electromagnetic wave) through the THz range filter based on multilayer structure “graphene–dielectric” with different number N of graphene sheets (N = 33, 47, 60) for the values of chemical potential \( \mu_c = 0 \text{ eV}, \mu_c = 1 \text{ eV} \) [21].

Figure 13. Frequency dependence of element \(|S21|\), dB, scattering matrix of the filters based on multilayer structures of type “graphene–dielectric” with different number of graphene sheets (N = 33, 47, 60) for values of the chemical potential \( \mu_c = 0 \text{ eV}; \mu_c = 1 \text{ eV} \); h = 3.65 \( \mu \text{m} \); \( \varepsilon_d = 2.2 \).

From the results of the electrodynamic calculation (figure 13) it follows that with increase of graphene sheets number (N = 33, 47, 60), the transmission coefficient |S21| in the non–transmission band decreases significantly. As the modelling results demonstrate, by changing the chemical potential \( \mu_c \) by the application of external electric field (which leads to change of graphene conductance), it is possible to control the characteristics of filters based on multilayer structures of type “graphene–dielectric”.

So, at chemical potential value \( \mu_c = 0 \text{ eV} \) (if external electric field absents), THz radiation attenuation in the non–transmission band is 2 – 4.5 dB (depending on the number \( N = 33 – 60 \), respectively). At application of external electric field, which corresponds to chemical potential \( \mu_c = 1 \text{ eV} \), the attenuation of radiation increases to 20 – 40 dB (with change in the number N of graphene sheets \( N = 33 – 60 \)).

Thus, from the results of modelling it follows that the investigated periodic layered microstructure of type “graphene–dielectric” can be used to create the broadband filters of sub–THz and THz band of...
planar construction, controlled by electric field and quickly tunable with small changes of the level of graphene Fermi energy [21].

5. Conclusions
Filters based on multilayer structures of type “graphene–dielectric” are controlled by changing the chemical potential by electric field displacement. In the absence of electric field, the filter transmits the corresponding radiation, in the presence of electric field—the attenuation of microwave, sub–THz or THz radiation can reach $\sim 40$ dB and above, depending on the number of graphene layers.

Model of the filter based on the multilayer structure of type "graphene – dielectric" is constructed. It is shown that such filter has stability and resistance in relation to the spread of the values of the surface conductance of graphene sheets included in the investigated filter.

The researched structures can be apply for creating of controlled wideband filters of microwave, sub–THz and THz ranges of frequency of planar design and construction. Rejection filters built on the base of multilayer structures of the "graphene–dielectric" type are particularly promising.

As modelling results show, changing the chemical potential by means of external electric field, which leads to change in the graphene conductivity, it is possible to control the transmission coefficient of radiation of the corresponding range through filters based on multilayer structures of the "graphene–dielectric" type.

References
[1] Chen P Y Soric J Padooru Y R Bernety H M Yakovlev A Al’u A 2013 Nanostructured graphene meta–surface for tunable terahertz cloaking New Journal of Physics 15 123029
[2] Fallahi A et al 2012 Design of tunable biperiodic graphene metasurfaces J Physical Review 86 195408
[3] Zhang Y Feng Y Zhu B Zhao J Jiang T 2014 Graphene based tunable meta–material absorber and polarization modulation in terahertz frequency J Optics Express 22 19 pp 22743–22752
[4] Chernozatonskiy L A Sorokin P B Artyukh A A 2014 New Graphene–Based Nanostructures: Physico–Chemical Properties and Applications Advances in chemistry pp 251–279 (In Russian)
[5] Isaev V M Kabanov V V Komarov V P 2014 Modern Radioelectronic Systems of THz Range Reports of TUSUR 4 (34) pp 5 – 21 (In Russian)
[6] Kivshar Yu S 2015 From meta–materials to meta–surfaces and meta–devices Nanosystems: Physics, Chemistry, Mathematics 6 3 pp 346–352
[7] Shi S F Zeng B Han H L Hong X Tsai H Z Jung H S Zettl A Crommie M F Wang F 2014 Optimizing broadband terahertz modulation with hybrid graphene /meta–surface structures Nano Letters 15 pp 372–377
[8] Innocenti R D Jessop D S Shah Y D Sibik J Zeitler J A Kidambi P R Hofmann S Beere H E Ritchie D A 2014 Terahertz optical modulator based on meta–material split ring resonators and graphene J Optical Engineering 57 108 pp 1–5
[9] Golovanov O A 1991 Diffraction on the Nonlinear Dielectric in the System of Connected Strip J Lines Radio Engineering 7 pp 65–70. (In Russian)
[10] Horng J Chen C F Geng B Girit C Zhang Y Hao Z Bechtel H A Martin M Zettl A Crommie M F Shen Y R Wang F 2010 J Physical Review 83 165113
[11] Yan H Li X. Chandra B Tulevski G Wu Y, Freitag M Zhu W Avouris P Xia F 2012 Tunable infrared plasmonic devices using graphene / insulator stacks J Nature Nanotechnology 7 5 pp 330–334
[12] Khromova I Andryieuski A Lavrinenko A 2014 Multilayer graphene for waveguide terahertz modulator Meta Conference p 3
[13] Li H J WangL L Zhang H Huang Z R Sun B Zhai X Wen S Ch 2014 Graphene–based mid–infrared, tunable, electrically controlled plasmonic filter J Applied Physics Express 7 (2)
Zhongchao W Xianping L Jianjun Y Rong H Yuebo L Wei W Hongzhan L Hongyun M 2016 Active plasmonic band–stop filters based on graphene meta-material at THz wavelengths J Optics Express 24 (13) pp 14344 –143451

Zhang H Cao Y Liu Y Li Y Zhang Y etc 2017 A novel graphene meta–material design for tunable terahertz plasmon induced transparency by two bright mode coupling J Optics Communications 391 pp 9–15

Wang J etc 2016 Recent advances in graphene–assisted nonlinear optical signal processing Journal of Nanotechnology 2016 pp 275–292

Wu Y Yao B C Feng Q Y Cao X L etc 2015 Generation of cascaded four–wave–mixing with graphene– coated microfiber J Photonics Research 3 2 pp 64–68

Ji M Cai H Deng L Huang Y Huang Q Xia J Li Z Yu J Wang Y 2015 Enhanced parametric frequency conversion in compact silicon– graphene micro–ring resonator J Optics Express 123 14 pp 18679–18685

Sun Y Qiao G Sun G 2014 Direct generation of graphene plasmonic polaritons at THz frequencies via four wave mixing in the hybrid graphene sheets waveguides J Optics Express 22 23 pp 22880–27891

Golovanov O A 2006 Autonomous Blocks with Virtual Floquet Channels and Their Application for Solving Applied Problems of Electrodynamics J Radio Engineering and Electronics 51 12 pp 1423 – 1430 (In Russian)

Golovanov O A Makeeva G S Varenitsa V V Electrodynamic calculation of transmission coefficients of the TEM–wave through the multilayer periodic structures monolayer of type "graphene–dielectric” in THz range J Izvestiya vuzov 4 (32) pp 123 – 137 (In Russian)