ADVANCED ELECTROMAGNETICS, Vol. 1, No. 2, August 2012

Cut wires grating — single longitudinal wire" planar metastructure to achieve microwave magnetic-type resonance in a single wire

Galina Kraftmakher[*], **Valery Butylkin**

Kotelnikov Institute of Radioengineering & Electronics RAS, Fryazino branch, Russia

E-mail:*gkraft@ms.ire.rssi.ru

Abstract

Here we present new metastructures consisting of a cut-wire grating and a single nonmagnetic longitudinal cut-wire orthogonal to grating's wires. Experimental investigations at microwaves show that these structures can provide strong magnetically-induced resonant response of the longitudinal cut-wire depending on the geometry in the case when a metastructure is oriented along the direction of the wave propagation and the cut-wires of the grating are parallel to the electric field of the incident plane electromagnetic wave. It is supposed that this response is due to the excitation of resonant currents by magnetic field of surface polaritons in many equivalent spatial *LC-circuits* formed by cut-wire pairs of the grating and sections of the longitudinal cut-wire. Three resonant effects have been separately observed and identified by measurements in waveguides, cutoff waveguides and free space. These effects are connected with the grating, *LC-circuits* and the longitudinal cut-wire. To distinguish and tune the resonances we use split cut-wires loaded with varactor diodes.

1. Introduction

We know, at microwaves metamaterals with conductive nonmagnetic chiral inclusions, can possess a effective magnetic permeability, which depends on the orientation of the inclusions with respect to the magnetic field **h** of the incident electromagnetic wave. Resonance phenomena are caused by the excitation of resonance currents by the field **h**. Presently extensive investigations are directed toward the development of magnetic metamaterials containing technologically simple line non magnetic wires to apply in dispersion engineering [1]. The main attention is devoted to a cut-wire pair that possesses both the electric and magnetic responses due to the possibility of parallel currents induction by the electric field and antiparallel currents, by the magnetic field [2, 3]. Since the magnetic and electric resonance responses are generated practically at the same frequency, it is difficult to separate these signals and evaluate the magnetic contribution. Term "parallel currents" means that induced currents in parallel wires flow in the same direction in contrast to "antiparallel currents", when induced currents flow in the opposite directions.

In paper [4] it is suggested a new way to create separately a strong microwave magnetically-induced resonance response using nonmagnetic cut-wires. Magnetic nature, magnetically-induced resonant response or magnetic-type resonance mean that resonance is due to the excitation of currents by electromotive force which is caused by the alternating magnetic field with accordance of Faraday's law of electromagnetic induction. Reductive expression "excitation of currents by magnetic field", is used rather often, e.g. [2] and references. Electric-type resonance means that resonance currents are induced by electric microwave field. In [4] it was found in waveguides that a line nonmagnetic wire of length l_m (fig. 1 a), which is oriented along waveguide axis parallel to the direction of propagation of an electromagnetic wave (and perpendicularly to its electric field **E**) and arranged asymmetrically near a grating of cut-wires l_p (*Grating*), can exhibit a resonance response of magnetic nature. *Grating* (wires l_p are parallel to the incident electric field **E**) forms surface polaritons bellow the resonance frequency in dependence on length l_p. Without the *Grating* there is not response of longitudinal wire l_m. Asymmetrical location corresponds to the position of longitudinal cut-wire l_m, when distance $t_1 \neq t_2$ in contrast to symmetrical location when $t_1 = t_2$. A giant resonance is observed in longitudinal single cut-wire l_m of a definite (resonance) length in a certain frequency range corresponding to the existence of surface polaritons. In this paper we investigate experimentally this very interesting phenomenon in waveguides (WG), cutoff waveguides (cutoff WG) and free space depending on the geometry. We suggest and verify a concept of magnetically-induced response based on possibility of resonant currents induction by magnetic field of surface polaritons in many spatial *LC-circuits* formed by *Grating's* cut-wire l_p pairs and sections of the longitudinal cut-wire l_m. In *LC-circuits* antiparallel currents flow in adjacent wires l_p while like-directed currents flow along the longitudinal cut-wire l_m. In this paper we demonstrate and identify three separately observed resonant effects. The first resonance is due to parallel currents induction in *Grating's* wires, the second resonance effect is due to the excitation of resonance currents in *LC-circuits* and the third resonance is due to the resonance current along longitudinal cut-wire l_m. Varactor-loaded split cut-wires are applied to tune and distinguish the resonances.

2. Investigated metastructures. Concept of the magnetically-induced response

Investigated metastructures consist of a grating of cut parallel copper wires with length l_p (*Grating*) and a single nonmagnetic (copper) longitudinal cut-wire (length l_m) which is placed perpendicularly to wires l_p on distance s (**fig. 1a**). One can imagine the metastructure as matter with many *LC-circuits* formed by cut-wire pairs of the *Grating* and sections of the longitudinal cut-wire. In the case when metastructure is placed along propagation direction magnetic-type resonance effects are observed. Obtained results allow to suggesting a concept of the resonance responses. Metastructures "*Grating* - single longitudinal cut-wire", "Wire pair – longitudinal cut-wire", "*Grating* - parallel cut-wire" are investigated depending on geometry. Metastructures with varactor-loaded split longitudinal cut-wire and split parallel cut-wire are also investigated.

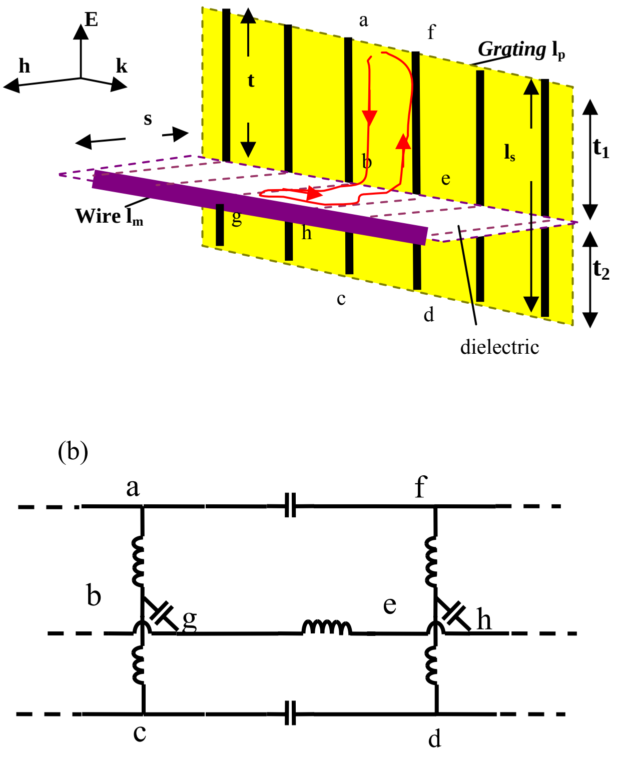


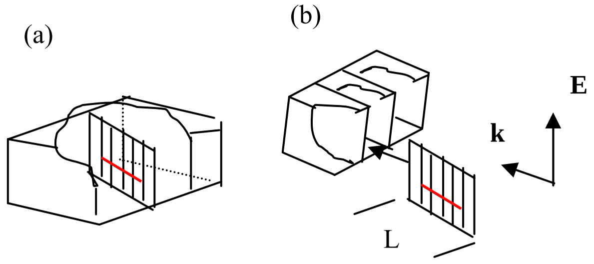
Fig. 1a,b. "*Grating* - single longitudinal cut-wire" metastructure (a)
and its equivalent electric diagram (b).

2.1 Measurements methods (waveguides, free space)

We have measured frequency dependence of the transmission coefficient *T* of electromagnetic wave of metastructures with panoramic standing-wave-ratio and attenuation meters R2-53 (3-6 GHz) and R2-61 (8-12 GHz). Metastructures are arranged along the axis and oriented parallel to the side wall of a standard rectangular waveguide (**fig. 2a**). Besides we have measured frequency dependence of the transmission coefficient *T* of electromagnetic wave with metastructures arranged in below-cutoff rectangular section. The measurements were performed in frequency range 3-6 GHz, in this case we used WG (48 x24 mm) and a below-cutoff rectangular section (16x24 mm). We have also used a standard waveguide (23x10 mm) and a below-cutoff rectangular section (8x10mm) to measure transmission in frequency range 8-12 GHz. To prepare below-cutoff rectangular section a fragment of the main WG (of the length *L*=25mm) is divided into three sections by metal spacers parallel to the direction of wave propagation. Investigated metastructure is placed into a central cutoff rectangular section (**fig. 2b**).

A comparative analysis of the signal transmission spectra in the main and below-cutoff rectangular section is an important method of identification of the type of excited resonance [5]. For example, in the case of magnetic excitation (magnetic-type resonance in WG, **MR**) the transparency band in cutoff WG is observed above the **MR** frequency. In addition, the magnetic excitation is characterized by the presence of super-forbidden band below the **MR.** In the case of electric excitation (electric-type resonance, **ER**), the transparency band in cutoff WG is observed below the **ER** frequency.

We have also measured the frequency dependence of the transmission coefficient *T* of metastructures arranged in free space in the gap between transmitting and receiving waveguides for two cases. In the first case receiving and transmitting WG are placed along the same axis (A-direction). In the second case receiving WG is placed along transverse B-direction (**fig. 2c**).



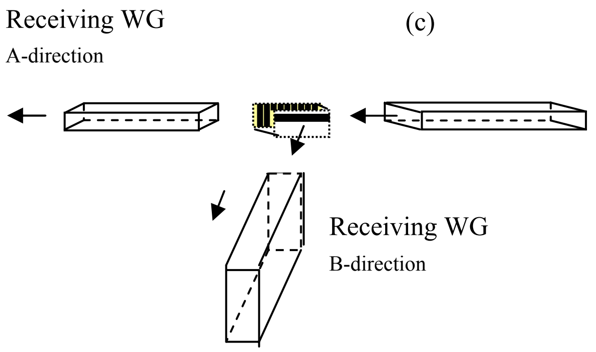
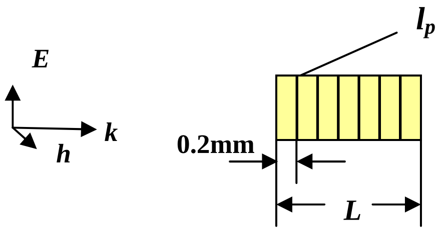


Fig. 2. Metastructure in (a) WG, (b) below-cutoff rectangular section and (c) free space.

2.2. Experimental verification

2.2.1. "*Grating* - single longitudinal cut-wire" metastructure

Below we present results of investigation of metastructure "*Grating* - single longitudinal cut-wire" (**Fig.1a**), like [4], placed along propagation direction of electromagnetic wave and engineered to have magnetic resonance properties using only cut-wires, l_p and l_m are lengths of grating's wire and longitudinal cut-wire, s – distance between *Grating* l_p and single wire l_m *Grating* (wires l_p are parallel to the **E**-field) exhibits a resonance response, which is manifested by resonance **I** of the electric-type and characterized by a resonance dependence of the transmission coefficient with a minimum at a certain frequency dependent on the wire l_p length. This *Grating* is excited by the **E**-field (induction of parallel currents) and generates surface waves (polaritons) near resonance **I** (below the resonance frequency). Local transverse magnetic field of polaritons induces electromotive forces and resonance currents in many spatial *LC-circuits* (such as *abghefa* and *cdehgbc* created from cut-wire pairs of *Grating* and sections of longitudinal cut-wire) and resonance current along longitudinal cut-wire.



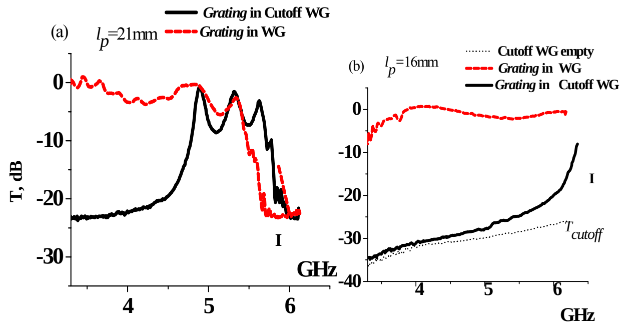


Fig.3. Frequency dependences of T in the WG (dashed curves) and cutoff WG (solid curves) in the presence of (a) Grating of l_p=21mm and (b) Grating of l_p=16mm.

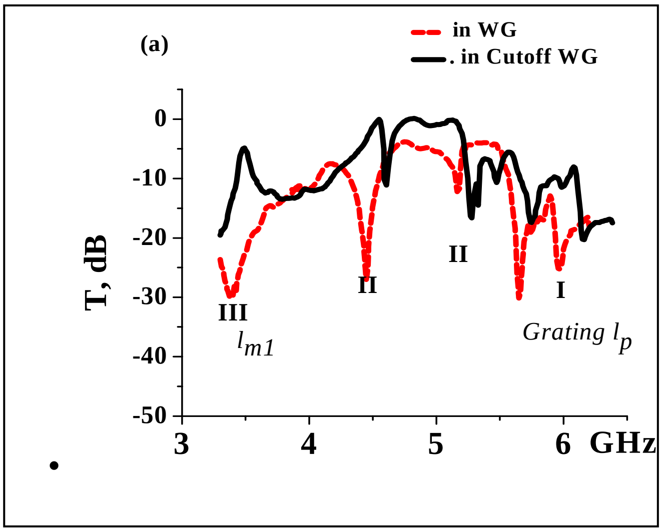
Equivalent electric diagram is shown in **Fig. 1b**. Directions of currents which flow in many *LC-circuits abghefa* are the same along wire l_m and opposed to currents of circuits *cdehgbc*. In the case of symmetrically located wire l_m (t=l_p/2) these opposed currents along longitudinal cut-wire of circuits *abghefa* and *abghefa* are practically quenched. In the case of asymmetrically location (t=l_p/4), if longitudinal cut-wire length l_m is resonant the wave of current along wire l_m and the resonance response are very strong.

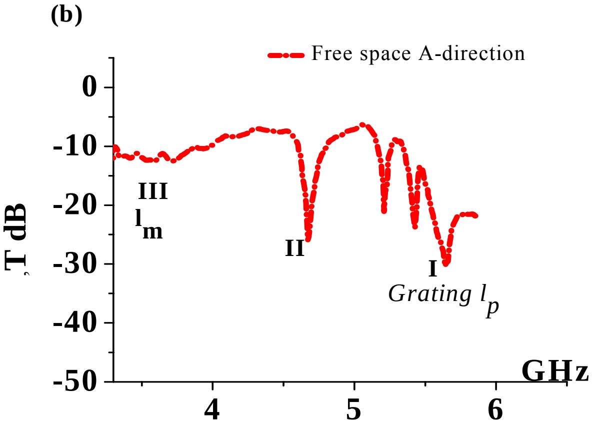
Resonance response of a longitudinal cut-wire l_m can be detected separately because its resonance frequency depends on length l_m and distance s and is different from frequencies of *Grating* and *LC-circuits*.

Results of measurements with *Gratings* without longitudinal wire are presented in **Fig 3a,b**. These *Gratings* are used in metastructures to achieve resonance effects in range 3 – 6 GHz. *Grating* with l_p=21mm allows to observe resonance effects connected with both *Grating*, *LC-circuits* and longitudinal cut-wire l_m. *Grating* with l_p=16mm is selected so as to shift resonance **I** to high–frequency edge of the interval of measurements and do not overlap with resonance connected with longitudinal cut-wire l_m. **Fig. 3a** shows the frequency dependences of transmission T measured in the presence of Grating of wires l_p=21mm, for which resonance **I** is observed in the WG at 6 GHz and pass-band is observed in the cutoff WG section at frequencies below this resonance. **Fig. 3b** shows corresponding frequency dependences of T measured in the presence of Grating of wires l_p=16mm, for which resonance **I** and pass-band (below **I**) are observed above 6 GHz in the WG and cutoff WG. Position of pass-band below the resonance **I** specifies electric excitation and electric-type resonance of the *Grating*.

Now let us consider the results of measurements in the presence of metastructure "*Grating* - single longitudinal cut-wire". In **fig. 4ab** we see frequency dependences of transmission T measured in WG, cut off WG and in free space in the presence of metastructures "*Grating* - single longitudinal cut-wire" with the same l_p=21mm, s=0.2mm, t= l_p/4 and l_m=26mm. In this case in addition to resonance **I** of the *Grating* of wires l_p the metastructure exhibits magnetic-type resonances **II** (of *LC-circuits*) and **III** (of single longitudinal cut-wire l_m), **fig 4a.** The below-cutoff section exhibits, besides pass-band due to *Grating* l_p, a new transparency band that extends from resonances **III** and **II** toward high-frequency region. Such position of pass-bands identifies magnetic excitation and magnetic-type of the resonance (**MR**). The resonance **II** is due to resonance currents in *LC-circuits* excited by transverse magnetic field of polaritons and resonance **III** is due to the total contribution of currents of *LC-circuits* along longitudinal cut-wire l_m.. Circular currents in *LC-circuits* form magnetic moments; resonance current in longitudinal cut-wire l_m induces electric dipole moment.

How can we make out the difference between resonances **II** and **III** and distinguish the resonance **III** of longitudinal cut-wire l_m? One can easy do it by measurement of transmission T in free space (A-direction). In this case (**fig. 4b**) resonance response of longitudinal cut-wire l_m in A-direction is practically not entered in contrast to responses of *Grating* l_p and *LC-circuits*. There is also the way to mark out the resonance response of a longitudinal cut-wire applying varactor diodes (see part **2.3**).





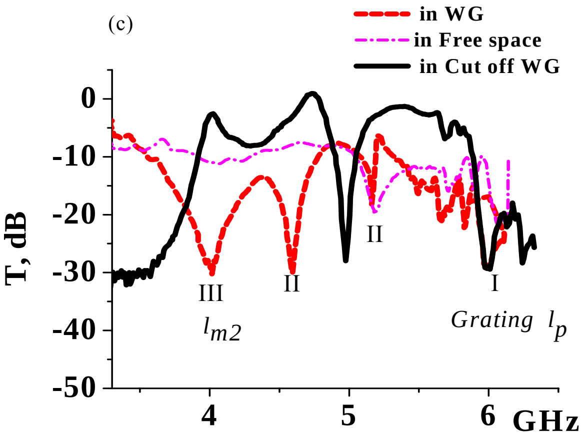


Fig.4a,b,c. Frequency dependences of T in the presence of "*Grating* -single longitudinal cut-wire" metastructure with l_p=21mm, s=0.2mm in WG (dashed) and cutoff WG (solid), in free space (dash dot): (a) l_{m1}=26mm and (b) free space (A-direction), (c) l_{m2}=24mm

The position of resonance **MR III** depends on length l_m. The resonance **III** is observed at frequency 3.4 GHz in the case of l_{m1}=26mm (**fig. 4a**). With decreasing l_m to l_{m2}=24mm resonance **MR III** shifts to higher frequencies and observed at 4 GHz **(Fig. 4c).**

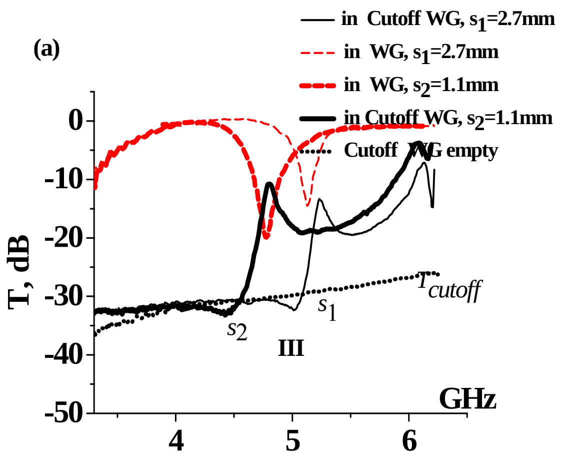
Fig. 5 shows frequency dependences of transmission measured in WG and cutoff WG (a,b) and in free space (c,d) in the presence of metastructure "*Grating* - single longitudinal cut-wire" with the same l_p=16mm, l_m=23mm, t= l_p/4 but different distance s. With l_p=16mm it is easy to observe how the resonance **III** shifts in dependence on s because resonance **I** and corresponding pass-band in cutoff WG would shift to the high-frequency edge of the interval of measurements and do not overlap with magnetic-type resonance **III** related to the l_m wire. Resonance **III** was excited at 5.1 GHz for a distance of s_1=2.7mm and shifted to lower frequencies (4.7 GHz) when s_2 was decreased to 1.1mm (**fig. 5a**). When s_3=0.2mm resonance **III** of l_m wire was observed at frequency 3.5 GHz (**fig. 5b).** The below-cutoff section exhibited the corresponding pass-bands (above frequency of the magnetic-type resonance **III** of l_m wire and supper-forbidden bands (below **III**, which occur at about 5 and 4.4 GHz and follow behind the shifting resonance **III**. Resonance **II** related to the *LC-circuits* was depicted at frequency 5.2 GHz in WG and free space (**fig. 5b,c**).

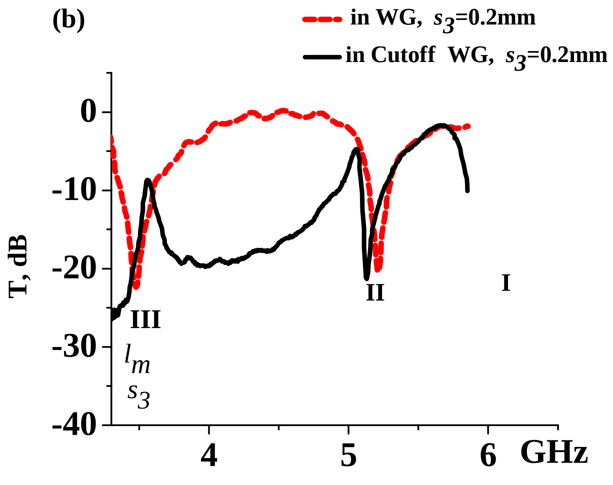
Resonance **III** of l_m is not depicted in free space in A-direction, but one can observe resonance response in B-direction by measurement of cross-polarized reflected wave from l_m wire, **fig. 5d.** In this case electric field of reflected wave is parallel to longitudinal cut-wire l_m and is orthogonal to the ***E*** -field of incident wave.

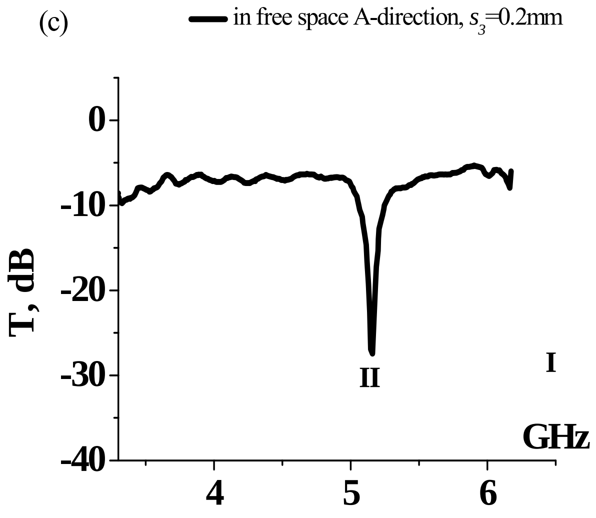
A strong resonance **III** is observed when the l_m wire is arranged asymmetrically (t =l_p/4), its intensity decreases when l_m wire shifts to symmetrically location. In the case of $t=l_p/2$ resonance response **III** is absent.

Strong **MR III** is observed if the l_m value is close to half-wavelength in the frequency region adjoining resonance **I** from the side of lower frequencies, which is the region of existence of surface polaritons generated by *Grating* l_p.

It is easy to prepare like structures to achieve magnetic-type resonance response of a single longitudinal wire l_m in different frequency ranges. Thereto it takes only to choose necessary lengths of wires l_m and l_p. **Fig. 7** shows the resonance **III** and dependence on wire l_m length in range 8 - 13 GHz. In the case of l_p =6mm and l_{m1} =11mm resonance **III** is observed at 8 GHz. The resonance **MR III** shifts toward higher frequencies (8.8 GHz) with decreasing l_{m1} to l_{m2}=9mm. Pass-band of the below-cutoff section in this case exhibits the corresponding shift and is observed above the resonance **MR III.**







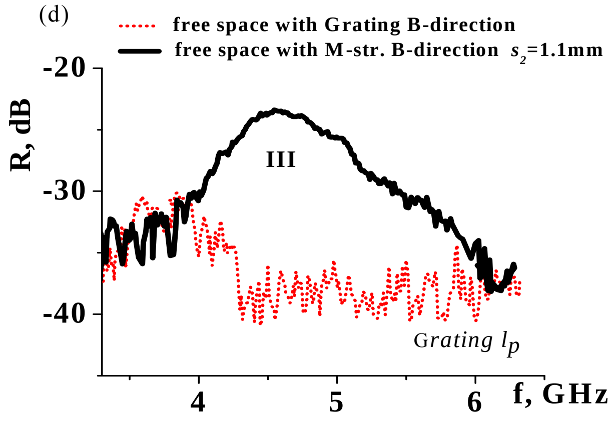
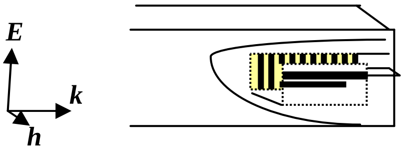


Fig.5a,b,c,d. Frequency dependences of *T* in the presence of "*Grating* - single longitudinal cut-wire" metastructure (l_p=16mm, l_m=23mm, s_1=2.7, s_2=1.1, s_3=0.2mm) in (a, b) WG (dashed) and cutoff WG (solid) and (c,d) free space (A- and B-directions).

In the case of metastructure with two longitudinal cut-wires l_{m1} and l_{m2} two **MRs III** are excited at different frequencies and two corresponding pass-bands (in cutoff WG section) appear above the resonances **III** (**fig. 6**). Resonance **MRIII** at frequency 4.1GHz is provided by wire l_{m1}=25mm and resonance at frequency 5.3GHz is provided by wire

l_{m2}=21mm. This experiment also confirms connection and dependence of resonance **III** on wire l_m length. Position of pass-bands confirms magnetic excitation and magnetic-type of the resonances **III**.

It is easy to prepare like structures to achieve magnetic-type resonance response of a single longitudinal cut-wire l_m in different frequency ranges (**fig. 7**). Thereto it takes only to choose necessary lengths of wires l_m and l_p. **Fig. 7** shows the resonance **III** and dependence on wire l_m length in range 8 - 12 GHz. In the case of l_p =6mm and l_{m1} =11mm resonance **III** is observed at 8 GHz. The resonance **MR III** shifts toward higher frequencies (8.8 GHz) with decreasing l_{m1} to l_{m2}=9mm. Pass-band of the below-cutoff section in this case exhibits the corresponding shift and is observed above the resonance **MR III.**



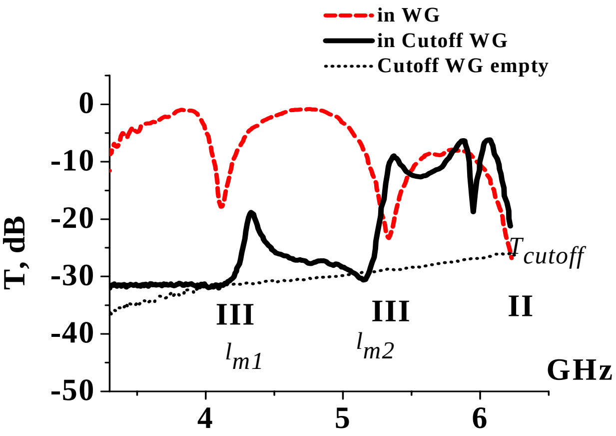


Fig.6. Frequency dependences of T in the WG (dashed) and cutoff WG (solid) in the presence of metastructure with two longitudinal wires l_{m1}=25mm and l_{m2}=21mm, l_p=16mm, s=1.1mm.

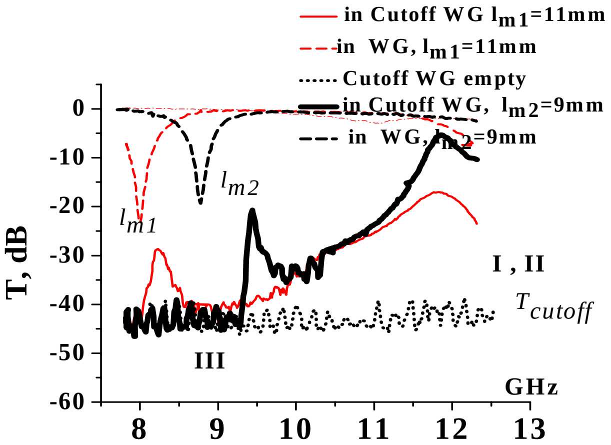


Fig.7. Frequency dependences of T in the WG (dashed) and cutoff WG (solid) in the presence of metastructure “ *Grating*-longitudinal cut-wire” with l_p=6mm, s=0.2mm: l_{m1} =11mm and l_{m2} =9mm

2.2.2. “Wire-pair – longitudinal cut-wire” metastructure

One can imagine *Grating* l_p as composition of many wire-pairs and confirm suggested conception by investigation of metastructure consisting one wire pair and longitudinal cut-wire. We investigate metastructure (see **fig. 8),** created from one pair of cut-wires **AB** in composition with asymmetrically located longitudinal cut-wire **CD** orthogonal to **AB** (wires AB are parallel to the electric field of incident electromagnetic wave). We show that this metastructure can also possess magnetic-type resonance of longitudinal cut-wire **CD** at frequencies different from electric resonance of cut-wires **AB.** Conditions to achieve magnetically-induced response and resonance properties are similar to the case of metastructure *“Grating*–longitudinal cut-wire”. In **Fig. 9a** we see frequency dependences of transmission *T* measured in WG and cutoff WG in the presence of metastructure “Cut-wire pair - longitudinal cut-wire”, distance *d* between wires **AB** is 20mm.

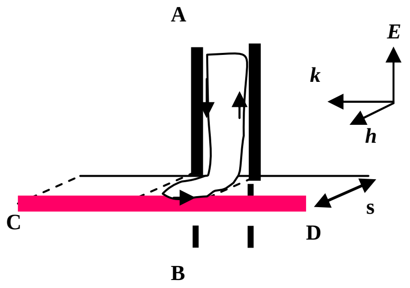


Fig. 8. Metastructure “Cut-wire pair-longitudinal cut-wire”

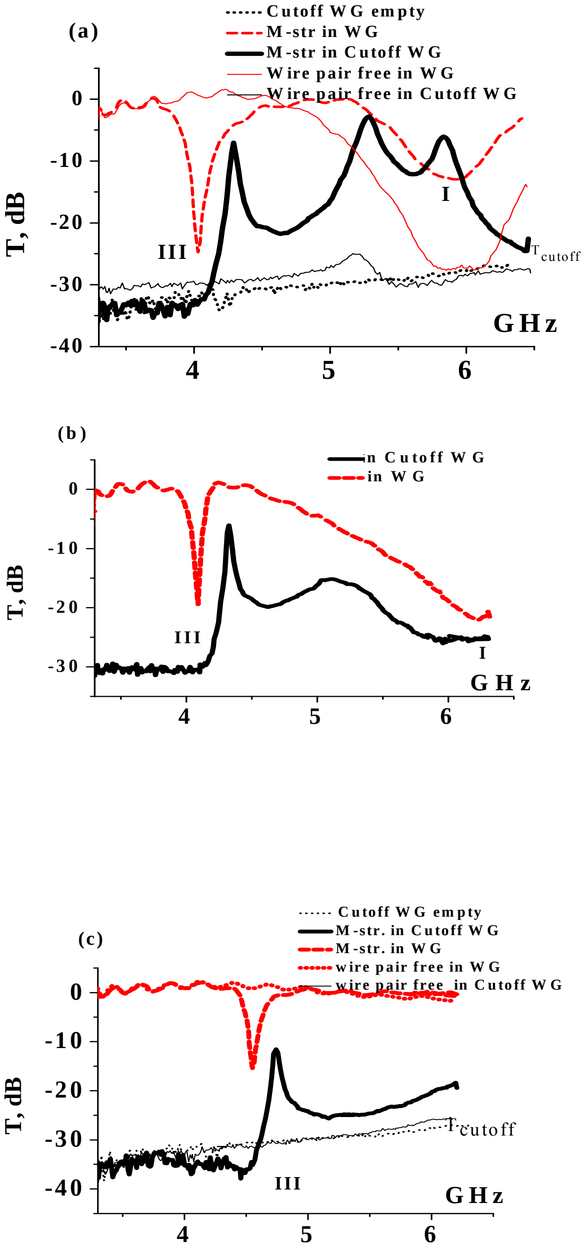


Fig. 9a,b,c. Frequency dependences of transmission T in the WG (dashed bold) and cutoff WG (solid bold) in the presence of metastructure *"Cut-wire pair - longitudinal cut-wire"*, d=20mm, s=1.1mm: (a) l_{CD}=29mm, l_{AB}=25mm, (b) l_{CD}=29mm, l_{AB}=22mm, (c) l_{CD}=26mm, l_{AB}=19mm

We observe in WG electric resonance **I** related to the wire pair **AB** without longitudinal wire **CD** at 6 GHz and corresponding pass-band in cutoff WG (below resonance **I**). In addition with "Cut-wire-pair - longitudinal cut-wire" metastructure we observe magnetic-type resonance **III** related to wire **CD** and corresponding pass-band in cutoff WG (above the resonance **III**), **fig. 9a**. With decreasing of the length l_{AB} resonance **I** shifts to the high-frequency edge of the interval of measurements and do not overlap with magnetic-type resonance **III** related to the **CD** wire (**Fig. 9 b,c**).

2.2.3. "Grating – parallel cut-wire" metastructure

Let us consider "*Grating* - single parallel cut-wire" metastructure created from grating of wires l_p and a cut-wire (marked l_e) located parallel l_p on distance s (**Fig. 10.**)

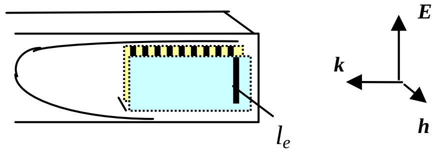
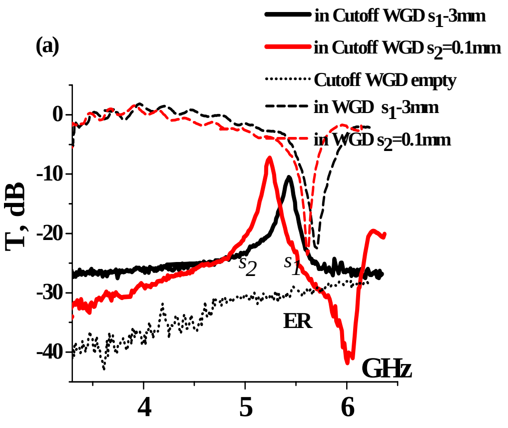


Fig. 10. Metastructure "*Grating*-parallel cut wire"

In this case electric-dipole resonance (**ER**) is excited, which depends on the wire length (l_e) and can be observed both with and without *Grating* l_p. The below-cutoff section exhibits a pass-band, which situated below the **ER** frequency and is characteristic of the electric excitation. In the case of strong change of distance s resonance frequency related to l_e wire is not practically shifted (**Fig. 11**) in contrast to **MR** frequency related to l_m wire (**Fig. 5a,b**).



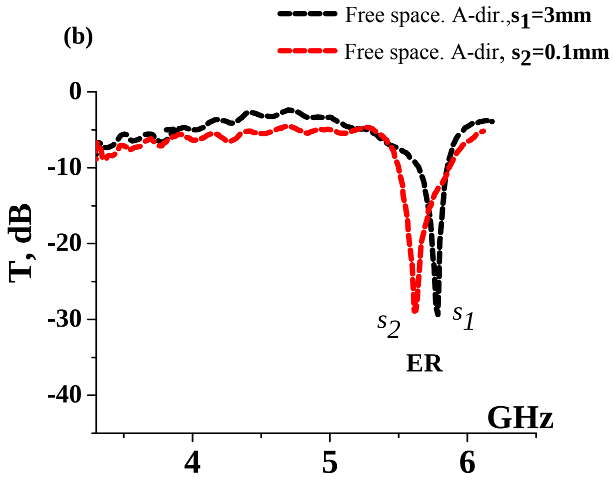
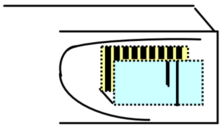


Fig. 11. Frequency dependences of transmission *T* in the presence of "*Grating*-parallel cut wire" metastructure, l_p=16mm, l_e=22mm, s_1=3mm, s_2=0.1mm in (a) the WG and cutoff WG and (b) free space A-direction

In the case of using two wires with different lengths l_{e1} and l_{e2} two **ER**s (**ER$_1$** and **ER$_2$**) are excited at different frequencies and two pass-bands (in cut off WG) appear bellow resonances **ER** that are characteristics of the electric excitation (**Fig. 12**).



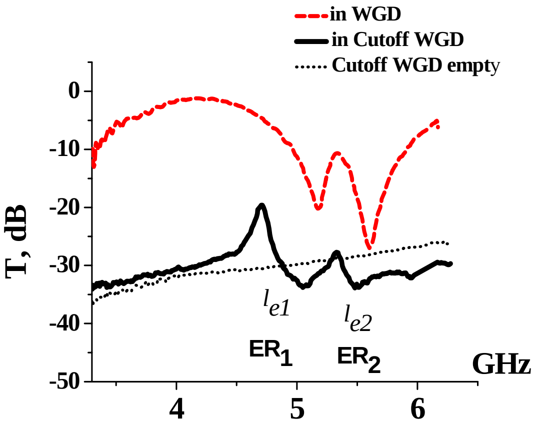


Fig. 12. Frequency dependences of transmission *T* in the WG and cutoff WG in the presence of "Grating - two parallel cut wires" metastructure: l_{e1}=23mm, l_{e2}=22mm

2.3. Split longitudinal cut-wire and parallel cut-wire loaded with varactor diodes

It is special interest to study a metastructure using varactor diodes. In [6] it has been demonstrated that the resonance frequency of split ring resonators (SRRs) can be tuned using varactor diodes. The resulting particle has been called a varactor-loaded split ring resonator (VLSRR). In this paper we use varactor diodes in metastructures to tune resonance response related to cut-wires and match the resonance minima of transmission *T* to concrete resonant elements with certainty what is important for multi-resonance system.

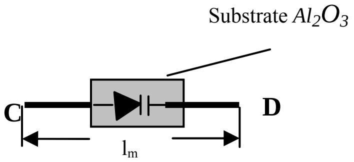


Fig. 13. Split cut-wire loaded with varactor diode

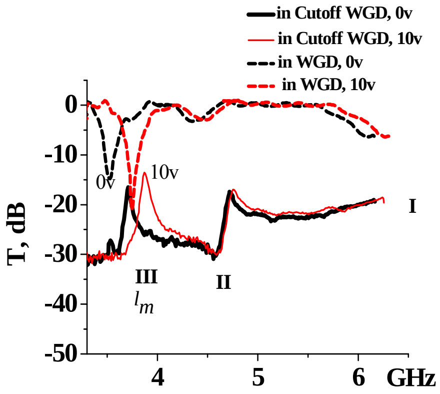


Fig. 14. Frequency dependences of transmission *T* in the WG (dashed) and cutoff WG (solid) in the presence of metastructure "*Grating* - varactor loaded split longitudinal cut-wire l_m" (l_m=32mm, l_p=16mm, *s*=3.5mm) under different bias conditions,

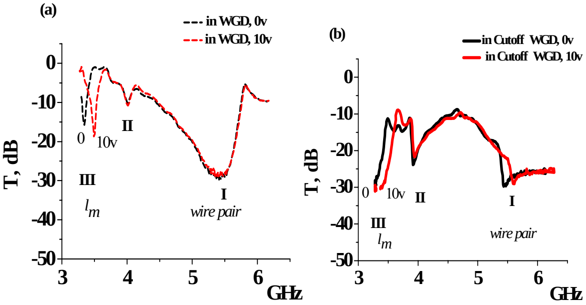


Fig. 15a,b. Frequency dependences of transmission *T* in the presence of metastructure "*Cut-wire pair*- varactor loaded split longitudinal cut-wire l_m" (l_m=32mm, l_{AB}=22mm, *s*=2.5mm) under different bias conditions in (a) WG and (b) cutoff WG,

By analogy with [7] we call resulting cut-wire as varactor loaded split longitudinal cut-wire l_m and varactor-loaded split parallel cut-wire l_e.

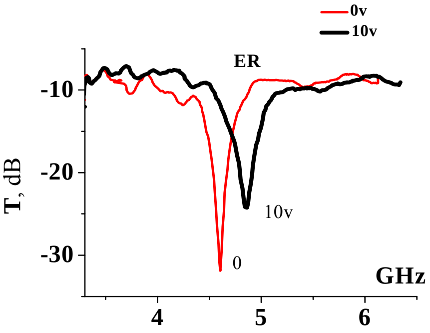


Fig. 16. Frequency dependences of transmission *T* in the presence of metastructure "*Grating* - varactor loaded split parallel cut-wire l_e" (l_e=32mm, l_p=16mm, *s*=1mm) under different bias conditions in free space A-direction,

Split longitudinal cut-wire is loaded with varactor diode placed on substrate Al_2O_3 in the gap as we see in **Fig. 13**. Frequency dependences of transmission *T* in the WG and cutoff WG in the presence of metastructures "*Grating*-varactor loaded split longitudinal cut-wire l_m" and "*Cut-wire pair* - varactor loaded split longitudinal cut-wire l_m" are demonstrated in **Fig. 14**, **15** under different bias conditions. These metastructures show electric resonance response **I** related to *Grating* l_p (or wire pair **AB**), resonance **II** and magnetic-type resonance **III** related to split longitudinal cut-wire l_m (or split cut-wire **CD**) loaded with varactor diode SMV1234. Resonance **III** of varactor loaded split longitudinal cut-wire l_m shifts from 3.53 GHz to 3.74 GHz (**Fig. 14**) and from 3.34 GHz to 3.49 GHz (**Fig. 15**) with the tuning voltage V_{DC} from 0 to 10v. Corresponding pass-band in cutoff WG (above **III)** follows the shifting resonance **III**. Positions of resonances **I** and **II** are practically not changed. Metastructure "*Grating*- varactor loaded split parallel cut-wire l_e" consists of *Grating* l_p and split cut-wire l_e loaded with varactor. This metastructure exhibits electric resonance response **I** related to *Grating* of wires l_p and electric resonance **ER** related to varactor loaded split parallel cut-wire l_e. **Fig. 16** shows that the resonance **ER** shifts from 4.6 GHz to 4.86 GHz with the tuning voltage V_{DC} from 0 to 10v corresponding to varactor tuning capacitance from 9.63 to 1.47 pF.

3. Discussion

Obtained results allow to suggesting a concept of magnetically-induced resonance response (magnetic-type resonance) based on excitation of resonant currents by electromotive force which, with accordance of Faraday's law of electromagnetic induction, is caused by the transverse magnetic field of surface polaritons in many equivalent spatial *LC-circuits* formed by cut-wire pairs of the *Grating* and sections of the longitudinal cut-wire l_m. Is there any possibility of traditional electric excitation of current in cut-wire l_m? Theoretically, yes, because near each cut-wire-end of the *Grating* there are electric field's longitudinal components in mutually opposite directions (parallel and antiparallel to the wave vector *k*). Therefore these components of the field can induce currents in opposite directions along the longitudinal cut-wire; so, total longitudinal current must be practically absent. Besides practically existence of the longitudinal electric field near the *Grating* has been not depicted [7] when double split ring was used as a probe for determining the orientations of surface polaritons local fields.

4. Conclusions

1. Microwave properties of new metastructures consisting of *Grating* with nonmagnetic cut-wires (length l_p) and a single nonmagnetic longitudinal cut-wire (length l_m) orthogonal to *Grating's* wires are investigated in waveguides, cutoff waveguides and in free space. The metastructure can be considered as composition of many *LC-circuits* formed by cut-wire l_p pair of the *Grating* and sections of the longitudinal cut-wire l_m. The metastructures are designed for the observation and investigation of microwave magnetic and electric resonance effects. Type of the resonance (magnetic-type resonance excited by magnetic field or electric resonance excited by electric field) can be identified using comparative analysis of the transmission in the main and below-cutoff waveguides.

2. Three separate resonance effects **I**, **II**, **III** are observed in the case when metastructure is oriented along propagation direction and cut-wires of the *Grating* are parallel to the electric field of the incident electromagnetic wave. The resonances are connected with *Grating* (resonance **I**), as well with both *LC-circuits* (resonance **II**) and longitudinal cut-wire l_m (resonance **III**).
It has been shown that metastructure exhibit electric-type resonance **I** of the *Grating* forming surface polaritons below the resonance frequency depending on length l_p. This resonance is due to the excitation of parallel resonance currents in cut-wires l_p by electric field.
It has been shown that metastructure exhibit magnetic-type resonance **II** of *LC-circuits* depending on length l_p and distance *s* between the longitudinal cut-wire l_m and the *Grating*.
It has been shown that metastructure exhibit magnetic-type resonance **III** in range of surface polaritons existence, depending on length l_m and distance *s*. This resonance is due to the excitation of resonance current in a single longitudinal cut-wire l_m.
3. Concept of magnetic-type resonances (magnetically-induced responses) is presented. The concept is based on the excitation of circular resonance currents in many equivalent spatial *LC-circuits* and corresponding induced magnetic moments by the transverse magnetic field of surface polaritons (resonance **II**). In this case antiparallel currents flow in the *Grating's* adjacent cut-wires l_p while like-directed currents flow along cut-wire l_m. Currents contribution of many *LC-circuits* provides strong resonance current and electric dipole moment along cut-wire l_m and strong resonance effect (resonance **III**).

So, presented metastructure containing nonmagnetic line cut-wires can possess induced magnetic and electric dipole moments and can exhibit magnetic-type resonances excited by magnetic field.

Using the observed phenomena, it is possible to create new magnetic metamaterials (in particular, those possessing magnetic permeability) tunable in a broad frequency range.

Acknowledgements

Acknowledgements. This study was supported by the RFBR, projects nos. 10-08-00018, and 11-02-90403.

References

1. Christophe Caloz, Metamaterial dispersion engineering: A new paradigm in microwave science and technology, pp. 1- 2, Proceedings of *Metamaterials'2010*, pp . , Karlsruhe, Germany, Sept. 13-18, 2010.
2. Shalaev, V. M., Kawata S., *Advances in Nano-optics and Nano-photonics. Nanophotonics with surface plasmons*, Elsevier, 2007.
3. Dolling, G., Enkrich, C. and Wegener, M., at al., “Cut-wire pairs and plate pairs as magnetic atoms for optical metamaterials,” *Optics Letters,* Vol. 30, No. 23, 3198-31200, 2005.
4. Butylkin, V. S., and Kraftmakher G.A., “Magnetic Type Resonance in Nonmagnetic Line Wire Excited by Surface Plasmons in Microwave Range,” *Tech. Phys. Letters*, Vol. 37, No. 4, 399–312, 2011; see also in *Proceedings* of *Metamaterials'2010*, Karlsruhe, Germany, 450-452.
5. Kraftmakher, Galina, “New realization and microwave properties of double negative material”, *Int. Journal of Applied Electromagnetics and Mechanics*, Vol. 19, Nos. 1-4, 57-61, 2004.
6. I. Gil, J. Garcia-Garcia, J. Bonache, F. Martin, M. Sorolla and R. Marques, “Varactor-loaded splt ring resonators for tunable notch filters at microwave frequencies”, *Electronics Letters,* Vol. 40, No. 21, 2004.
7. V.S. Butylkin, G.A. Kraftmakher, S.L. Prosvirnin, “Method of Surface Polariton Field Structure Measurement Using Resonance Excited in a Single Planar Double Split Ring”, *Tech. Phys. Letters*, Vol. 38, No. 2, 147–150, 2012, see also in *Proceedings* of *Metamaterials'2011*, Barcelona , Spain, P.582-584.