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The effect of plasma on resonant scattering of a magnetic field by a dielectric ring

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The resonance scattering spectra on the main magnetic mode of structures made of a subwavelength dielectric thin ring and a low-pressure discharge plasma in a linear fluorescent lamp and a spiral lamp excited by an incident plane electromagnetic wave of the microwave range have been experimentally studied. It was found that when the discharge is turned on, the amplitude of the magnetic field induced by the ring at the resonant frequency of the ring decreases significantly. The reduction effect is realized with a certain orientation of the discharge relative to the ring. Computer simulation confirms the effect of reducing the magnetic field induced by the ring at the resonant frequency. An electric discharge can be used to switch the resonant electromagnetic fields of dielectric elements in filters, antennas, and energy redistribution systems.

Keywords: low pressure discharge, dielectric magnetic dipole, negative magnetic response, dielectric ring, plane microwave, resonance.

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Introduction

Resonant elements of different types [9–11] are used to create metamaterials [1], metasurfaces [2] for antennas [3–5], radiation filtration and redistribution systems [6, 7] and ideal lenses [8]. The first metamaterials were created on the basis of a resonant LC circuit in the form of a metal ring with a thin slit [12, 13], the properties of which are well-known, and the resonant parameters can be calculated based on capacitance, self-inductance, and magnetic fields from the Biot-Savart-Laplace law. Based on these elements, a large number of designs have been created for the microwave field, specifically in filter and antenna engineering. Replacement of metal meta-elements with dielectric ones is one of the ways to reduce dissipation losses at high frequencies. However, even in simple dielectric bodies, for example, a sphere, disk, or cylinder, when interacting with an electromagnetic wave,

different types of resonances are excited, the frequencies of which can coincide; therefore, the calculations of resonance frequencies and scattering fields for dielectric bodies are becoming a complicated problem [14–19]. Prior studies have shown that a sub-wavelength dielectric ring is an ideal magnetic-type dipole [20] with a fundamental resonance frequency that can be calculated from the concepts of capacitance and self-inductance, and scattering fields from the Biot-Savart-Laplace law. Therefore, the dielectric ring can be used in structures that have already been created based on a metal ring dipole.

The aim of this work was to study the resonance magnetic field of a system made of a dielectric ring and a plasma element in the form of a positive column of a low-pressure discharge under the excitation of a flat EM-wave in the microwave range.

Results of experiments and computer simulation

The scheme for conducting experiments on measuring the magnetic fields of the structure of a dielectric ring and an additional conductive element excited by a flat electromagnetic wave was similar to the one used before [21]. The driving generator was one of the channels of an Agilent E5071C ENA network analyzer, the signal from which was transmitted to an amplifier (20 dB) and then to an ETS-Lindgren's model 3115 horn antenna that formed a flat linearly polarized wave. Magnetic fields were measured with a Beehive Electronics 100B EMC probe with an internal diameter of the detector ring of 3.7 mm, the signal from which was sent to the input of the Agilent E5071C ENA network analyzer. A flat microwave excited the system of the dielectric ring ($\epsilon = 149$, $\text{tg}\alpha = 0.0003$, external diameter of 38 mm, internal of 28 mm, height of 5 mm) and the plasma element. Straight and spiral fluorescent lamps were used as the plasma element.

Fig. 1 shows the system of the dielectric ring located on top of the spiral lamp with a power of 13 W, and external diameter of the rings of 38 mm, and a plasma diameter of 7 mm. The ring with the lamp was located at a distance of 25 cm from the antenna in such a way that the wave vector and electric field vector of the flat incident wave were parallel to the plane of the dielectric ring and the rings of the gas-discharge tube, while the wave magnetic field vector was perpendicular. The dielectric ring was placed either directly on the lamp or above the top lamp ring at a distance of 5 mm. Since the lamp spiral is structurally folded at the end, the dielectric ring is closely adjacent only to a half-ring of the lamp spiral. The magnetic field probe was located on the side of the dielectric ring farthest from the antenna. The distance from the ring edge to the probe was 10 mm, therefore, the probe measured the resonance spectrum of the transmitted signal in the near zone of the ring. The plane of the magnetic probe ring was perpendicular to the

vector of the magnetic field and parallel to the wave vector and vector of the electric field of the incident wave.



Fig. 1. Photo of the dielectric ring system on the spiral lamp. The magnetic field probe is located on the right

Experimental results of the measurement of the magnetic field spectra of the ring and the spiral lamp are shown in Fig. 2. When the lamp is off, a standard resonant peak of the magnetic dipole is observed (curve 1). When plasma is created in the lamp (the lamp is on), the resonant peak disappears (curve 2). Curve 3 is the background signal from the probe when there is no ring and the lamp is off. The turned-on lamp with plasma (without the ring) slightly shields the transmitted signal (curve 4). With other arrangements of the dielectric ring near the spiral lamp, no such strong attenuation effect at the resonance frequency is observed. Consequently, the effect of the interaction of the fields of the dielectric ring with the plasma half-ring occurs only when the induced electric field in the dielectric ring interacts closely with the plasma in the lamp, as a result of which an induced current with energy dissipation passes through the plasma. If the interaction length is small, the attenuation is also small. If the ring is removed from the lamp by 5 mm, the effect weakens dramatically. Thus, the plasma element in the form of a low-pressure electric discharge can act as a switch with the help of which one can turn on and turn off the resonant element.

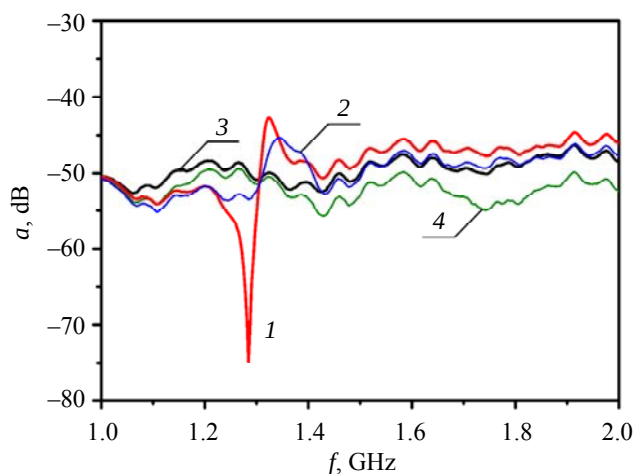


Fig. 2. Measured magnetic field spectra. 1 – ring on a lamp without plasma (red line 1); 2 – ring on a lamp with plasma (blue line 2); 3 – without the ring, lamp without plasma (black line 3); 4 – without the ring, lamp with plasma (green line 4)

Based on the lamp power and current, the average electron concentration is about 10^{13} cm^{-3} at a standard electric field strength in the column of about 1 V/cm; therefore, the plasma frequency is orders of magnitude higher than the range of resonance frequencies of the dielectric ring. Consequently, the experiments and computer simulation can be conducted using a copper wire in the form of a half-ring instead of plasma placed on top of the dielectric ring. To isolate the scattered component of the magnetic field of the studied system, a measurement of the level of background radiation, initiated by the wave with the probe in the absence of the test objects, is conducted. Then the background signal was subtracted from the signal measured in the presence of the test elements. The computer simulation was conducted using the CST Microwave Studio software. The calculation parameters were set in accordance with the experimental conditions for the copper wire (conductivity 58 mln Sm/m) with a diameter of 2 mm in insulation with a thickness of 0.7 mm. The half-ring was located in different positions on the dielectric ring. The results of the experiments and calculations with the copper half-ring located with the bulge towards the probe are shown in Fig. 3. It can be seen that the calculated and experimental resonance spectra of a single dielectric ring match well in frequency (curves 1 and 2). When adding a copper half-ring, the resonance frequency shifts towards low frequencies and decreases in amplitude both in the experiments and calculations (curves 3 and 4). A decrease in the resonance frequency is associated with an increase in the effective capacitance in the resonant circuit when adding

the metal half-ring. In the case of plasma, energy dissipation also occurs; therefore, the amplitude of the scattered magnetic field is strongly attenuated.

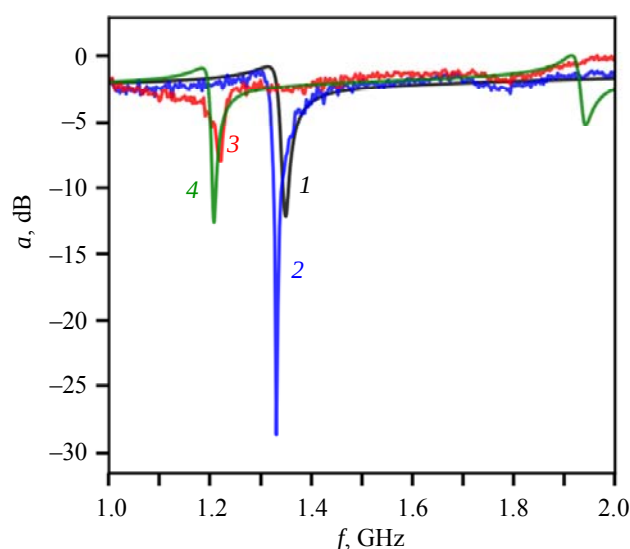


Fig. 3. Resonance magnetic field spectra for the dielectric ring and the half ring made of copper wire with a diameter of 2 mm in the insulation of 0.7 mm with a bulge towards the probe. The distance from the ring to the probe is 30 mm: 1 (black) – calculation, single dielectric ring, $f_0 = 1.350 \text{ GHz}$, $a_0 = -11.832 \text{ dB}$; 2 (blue) – experiment, single dielectric ring $f_0 = 1.331 \text{ GHz}$, $a_0 = -28.675 \text{ dB}$; 3 (red) – experiment, metal half-ring $f_0 = 1.222 \text{ GHz}$, $a = -7.903 \text{ dB}$; 4 (green) – calculation, copper half-ring $f_0 = 1.208 \text{ GHz}$

Systems with the dielectric ring and linear low-voltage lamps with powers of 12 W and 15 W, diameters of 12.5 mm and 26 mm, and lengths of 370 mm and 430 mm, respectively, as well as copper wires of different lengths, have been studied during the lamp replacement. The

lamp or copper wire was located right after the dielectric ring, perpendicular to the wave vector and parallel to the electric field vector of the incident microwave. The probe was located after the lamp or the conductor at a distance of 30 mm from the ring. An example of the experimental results and calculations for the system of the ring and the copper wire with a half-wave length at the resonance frequency (115 mm) is shown in Fig. 4. The calculated and experimental spectra match well in the resonance frequency (curves 1 and 2). When adding a wire behind the ring, the amplitude of the magnetic field is attenuated at the resonant frequency both in the experiment (curve 3) and in the calculations (curve 4).

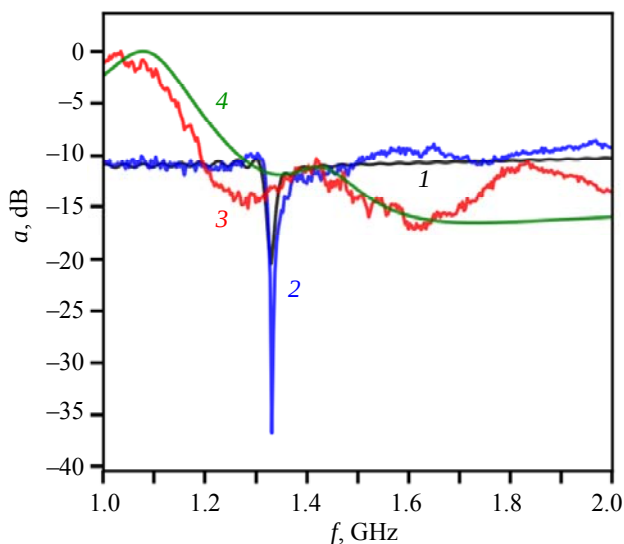


Fig. 4. Resonance spectra of the magnetic field for the ring and the half-wave straight conductor (115 mm):
 1 (black) – calculation, single dielectric ring, $f_0 = 1.350$ GHz, $a_0 = -11.832$ dB; 2 (blue) – experiment, single dielectric ring $f_0 = 1.331$ GHz, $a_0 = -28.675$ dB; 3 (red) – experiment, ring with conductor; 4 (green) – calculation, ring with conductor

It is worth noting that the attenuation of the resonant amplitude of the magnetic field occurs only with a certain lamp orientation relative to the dielectric ring. If the ring is placed on the lamp, i.e. the axes of the lamp and the ring coincide, the lamp does not affect the spectrum. There is no effect if the lamp axis is parallel to the magnetic field or in other lamp positions near the ring. The lamp and the conductor have the greatest influence in the position when they are parallel to the electric field vector. If the conductor or lamp is parallel to the wave vector, then they affect the resonant spectrum of the ring only in the case

when part of the lamp or the wire is on the left or right side of the ring, i.e. they can interact with the electric field of half the ring. If a lamp or wire passes through the center of the ring, there is no impact. Therefore, a straight lamp or a straight conductor can interact either through the circular electric fields of the ring, as in the case of a spiral lamp, or create an additional resonant system and shield the passing wave induced by the resonant field of the dielectric ring. In the second case, high-conductivity turns out to be a more important factor than attenuation in the plasma, which is confirmed by the calculations. Therefore, a plasma element in the form of a straight lamp can also turn on or off a passing resonant wave or resonant magnetic field. Such switches can be used in filters, antennas, and distribution systems of microwave energy.

Conclusion

The resonant scattering spectra of the dielectric ring – plasma element system have been studied. It was found that when the discharge is switched on, the attenuation of the amplitude of the scattered resonant magnetic field of the ring increases sharply. Experimental and computer modeling involving the replacement of plasma with a copper wire showed that in the case of half-ring, the resonance frequency shifts and the amplitude attenuates. In the case of a straight wire and a straight lamp, there is a resonant interaction of the incident plane EM-wave not only with the dielectric ring but also with the straight wire, as a result of which the strongest interaction occurs in cases when the wire length is a multiple of a quarter of the wavelength at the resonant frequency. It was found that the resonance shift and the attenuation of the resonant scattering occur only at a certain orientation of the plasma column relative to the dielectric ring, when the vector of the induced electric field strength is parallel to the discharge axis. Therefore, the plasma element can be used as a switch with the help of which one can turn on and off resonant scattering fields from the dielectric ring. Such switches can be used for switching resonant filters and for the redistribution of the microwave radiation fluxes in antenna technologies.

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