Extraordinary grating-coupled microwave transmission through a subwavelength annular aperture

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Abstract:
We studied coupling phenomena between surface plasmons and electromagnetic waves in the microwave spectrum using circular apertures surrounded by array of grooves. We first present experimental and theoretical results of enhanced microwave transmission though a subwavelength circular aperture with concentric periodic grooves around the surface plasmon resonance frequency. This is followed by transmission studies through circular annular apertures and circular annular apertures surrounded by concentric periodic grooves. We demonstrated that 145 fold enhancement factor could be obtained with a subwavelength circular annular aperture surrounded by concentric periodic grooves. Our results show that, high transmission from a circular annular aperture with grooves is assisted by the guided mode of the coaxial waveguide and coupling to the surface plasmons.

OCIS codes: (240.6680) Surface plasmons, (230.1950) Diffraction gratings

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1. Introduction

Surface plasmons (SPs) are collective excitation of the electrons at the surface of a conductor. As SP modes have longer wave vectors than light waves of the same energy, electromagnetic radiation does not interact with the SP modes of a smooth metal surface [1]. Therefore, the transmission of light through an aperture in a metal film is extremely small when the aperture diameter is much smaller than the wavelength. When the metal surface surrounding the subwavelength hole is corrugated, the incident light can couple to SPs. A resonant interaction leads to an enhanced transmission at wavelengths determined by the corrugation period [2, 3]. In 1998, Ebbesen *et. al.* [4] experimentally demonstrated that an extraordinary transmission of light could be obtained through subwavelength hole arrays in metallic films. Their results have stimulated new research dedicated to the subject of enhanced transmission through 1-D [5-10] and 2-D [11-15] periodic grating structures. In 2002, Baida *et. al.* [16] proposed a new structure: subwavelength annular aperture arrays exhibiting high transmission. Theoretical simulations by this research group have shown that the transmission efficiency could reach 80 % in the visible spectra range and a guided mode in the annular aperture was responsible from this large transmission [16, 17]. Recently, they also show that it was possible to enhance optical transmission using a subwavelength annular aperture surrounded by array of grooves [18]. However, all of these results are theoretical predictions, and to our knowledge experimental demonstration of enhanced transmission through a subwavelength annular aperture with concentric periodic grooves was not previously reported in scientific literature.

In this work, we experimentally and theoretically studied enhancement of radiation through a subwavelength circular aperture surrounded by concentric periodic grooves. We also investigated the high transmission assisted by the guided mode of the circular annular aperture. Furthermore, we presented extraordinary enhancement of microwave transmission through a subwavelength circular annular aperture surrounded by concentric periodic grooves.

2. Experiment and analysis

SP modes can interact with the electromagnetic radiation on a metal surface with periodic corrugations. Coupling of incident radiation to the surface plasmon waves on the grating structure is given by the equation:

$$k_{sp} = k_o + N k_g \tag{1}$$

Here k_{sp} is the SP wave vector, k_o is the portion of the incident wave vector that lies in the plane of the metal, N is an integer and is $k_g = 2\pi/\lambda_g$ is grating wave vector where λ_g is the grating

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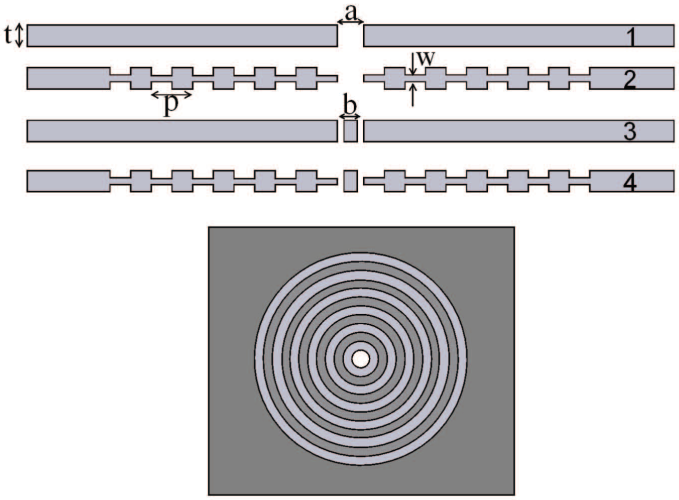

Fig. 1. Schematics of the four studied structures with t=8 mm, a=8 mm, p=16 mm, w=3.2 mm and top view of Sample 2.

period. A resonance occurs when this condition is satisfied and the transmission is strongly enhanced compared to a smooth metal with a small aperture. SP wave vector is calculated by the formula:

$$k_{sp} = k_o \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{2}$$

where ε_m and ε_d denote the permittivity of metallic an dielectric media respectively (ε_d is 1 for air). For microwave frequencies permittivity of metals are high ($\sim 10^6$), compared to the permittivity of air; so $k_{sp} \cong k_o$ in microwave range. Since the radiation is normally incident to the grating, coupled wave vector should be multiples of k_g. These equations hold for rectangular geometries such as hole arrays [4, 19], square grating structures [9, 10]. The surface plasmon mode is different in cylindrical geometries. Studies by Ebbesen *et. al.* and Lockyear *et. al.* showed that this equation gives pretty close values for the surface plasmon mode of cylindrical geometries [7, 14].

The experimental setup consisted of an HP 8510C network analyzer and two standard gain horn antennas to measure the transmission amplitude. Radiation was normally incident upon the sample from 15 cm by source antenna. Receiver antenna was 10 cm away from the sample. Schematic description of the studied structures is shown in Fig. 1. All four metallic (aluminum) structures had a hole in the center with diameter (a) 8 mm. The hole sample (Sample 1) with thickness (t) 8 mm was used as reference sample for transmission measurements. Second sample had the identical aperture surrounded by six rectangular grooves. Period of grooves was 16 mm and the thickness of the grooved metal (w) is 3.2 mm. Measurements were done in the microwave spectrum of 10-18 GHz, corresponding to a wavelength region of 16.7-30 mm.

Calculated and measured transmission results for Sample 1 and 2 are shown in Fig. 2. The experimental results are in good agreement with FDTD calculations. For Sample 2, a transmission peak was measured between 12.9 and 14 GHz with a transmission amplitude of 0.025. But for Sample 1 transmission was below 0.0025. It can be easily seen that the transmission around 13 GHz is enhanced by coupling to the SPs. Figure 3 shows the enhancement of transmission

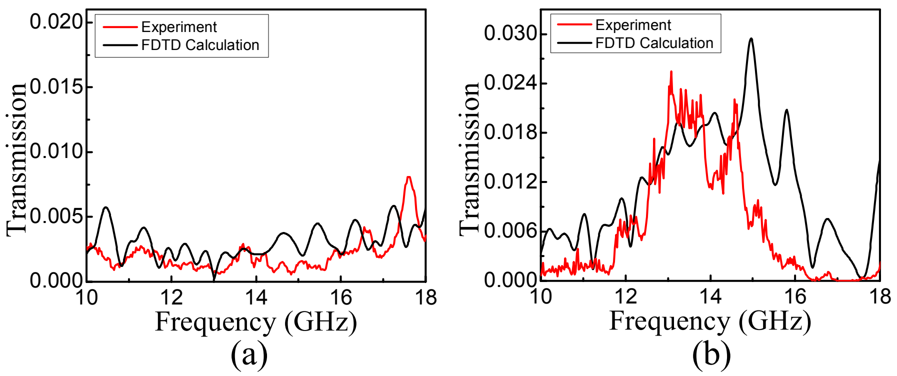

Fig. 2. Calculated and measured transmission results for a) Sample 1 and b) Sample 2.

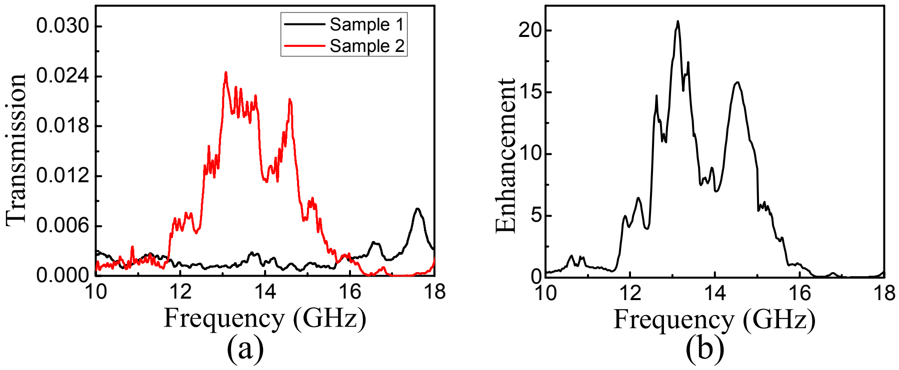

Fig. 3. a) Transmission results for Sample 1 and 2. b) Enhancement factor obtained with Sample 2.

according to the reference sample (Sample 1). 20 fold enhancement was obtained around SP resonance frequency with Sample 2.

Transmission through an annular aperture (coaxial waveguide) was studied recently by Baida *et. al.* [18]. It has been shown theoretically that at some wavelengths transmission through a coaxial waveguide was enhanced with respect to circular aperture. Coaxial waveguide have a TEM$_o$ mode without cutoff. So this structure is similar to a slit structure which can support a waveguide mode without cutoff. But TEM mode cannot be excited with a linearly polarized incident beam. The dispersion relation for other propagating modes (TE, TM) of a coaxial waveguide is given by:

$$k_z^2 = \frac{4\pi^2}{\lambda^2} - \frac{4\pi^2}{\lambda_c^2} \tag{3}$$

where λ_c is the cutoff wavelength of the mode. This cutoff for TE modes is given by:

$$\lambda_{cTEm,1} = \frac{\pi(a+b)}{m} \tag{4}$$

where a and b are the outer and inner radii of the coaxial waveguide. For $k_z = 0$ the eigenwavelengths are equal to the cutoff wavelengths ($\lambda_{mode} = \lambda_c$).

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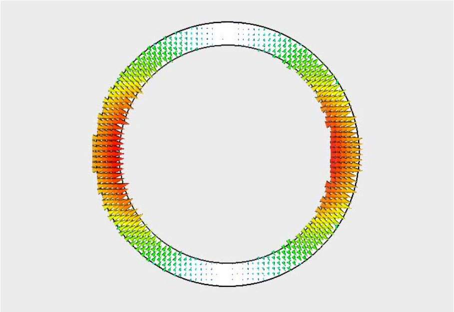

Fig. 4. Electric field distribution of Sample 3 at resonance frequency (13.2 GHz). Red indicates the maximum and blue refers to the minimum.

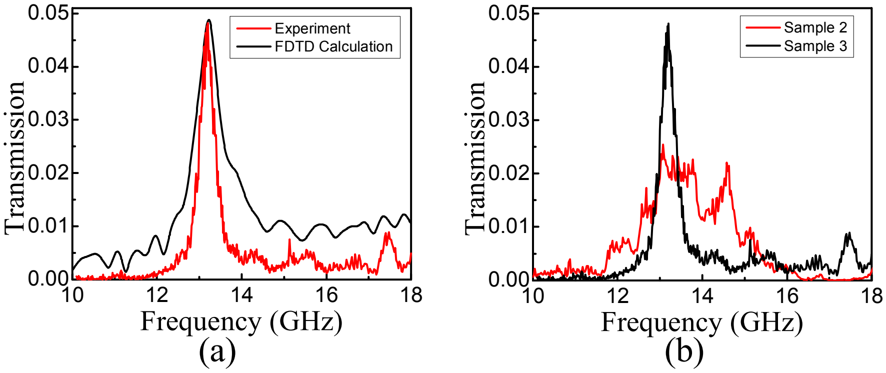

Fig. 5. a) Calculated and measured transmission results for Sample 3. b) Transmission results for Sample 2 and 3.

We designed an annular aperture which can support a mode around 13 GHz. Our structure (Sample 3) is identical to Sample 1 with a rod inside the hole. The diameter of the rod is 6.6 mm and thickness of the rod is 8 mm. The schematic of the sample is shown in Fig. 1. We calculated the electric field distribution at 13.2 GHz (Fig. 4). It can be easily seen that annular aperture have a TE mode at 13.2 GHz. Moreover, we measured transmission through Sample 3, these results agreed well with the calculated results (Fig. 5(a)). Figure 5(b) shows that transmission at the TE mode frequency from Sample 3 is higher than the transmission from Sample 2 at the SP resonance frequency.

In order to obtain even higher transmission, we combined the annular aperture and grooved structure (Sample 4). Calculated and measured transmission (Fig. 6(a)) of annular aperture surrounded by concentric periodic grooves show extraordinary high transmission at 12.9 GHz (23.25 mm). In Fig. 6(b) enhancement factor obtained with Sample 4 with respect to Sample 1 is presented. A maximum enhancement factor of 145 fold was obtained. Note that the area of the hole is also reduced by a factor of 3.13 with respect to Sample 1. If we include the reduction in the area of the aperture, $\sim$ 450 fold enhancement was obtained through the subwavelength annular aperture.

Such concentric periodic grooved structures with a very large transmission have many potential applications in photonic devices. They can be used for high-brightness subwavelength light sources or high-throughput optical switches.

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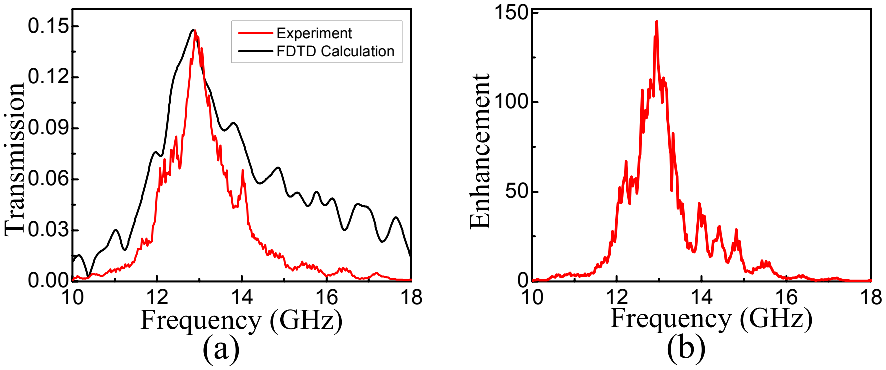

Fig. 6. a) Calculated and measured transmission results for Sample 4. b) Enhancement factor obtained with Sample 4.

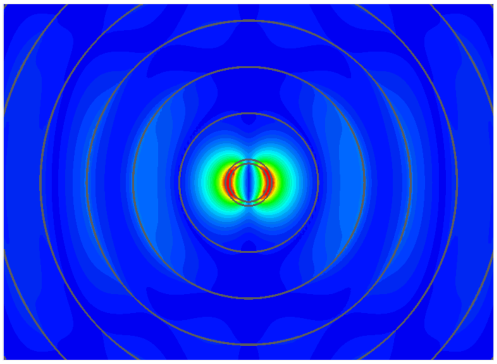

Fig. 7. Electric field distribution on the surface of Sample 4 at resonance frequency (12.9 GHz). Red indicates the maximum and blue indicates the minimum. Phase of the field changes by 5 degrees. (GIF-video file, 509 KB)

3. Conclusion

In conclusion, we presented measured and calculated results of microwave transmission through a subwavelength circular aperture with concentric periodic grooves. 20 fold enhancement was measured around the SP resonance frequency for subwavelength circular aperture with grooves. We also studied structures with circular annular aperture. Our results show that, high transmission from a circular annular aperture is assisted by the guided mode of the coaxial waveguide. Moreover, a remarkable 145 fold enhancement of transmission was observed with a subwavelength circular annular aperture surrounded by concentric periodic grooves via the coupling to the SPs and the guided mode of annular aperture. These results were verified by FDTD calculations.

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