# Surface wave splitter based on metallic gratings with sub-wavelength aperture

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**Abstract:** We investigated the splitting of surface electromagnetic waves trapped at the output surface of a one-dimensional metallic grating structure. The output gratings of the structure asymmetrically such that the output surfaces at the different sides of the subwavelength aperture can support surface waves at different frequencies. The transmission amplitude as measured at the left side is 1,000 times of that at the right side at 16 GHz. At 24 GHz, the transmission measured at the right side is 20 times that of the left side of the structure. Therefore, surface waves are guided into the different sides of the aperture at different frequencies via metallic gratings. The experimental results are in agreement with the theoretical results.

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**OCIS codes**: (240.240) Optics at surface: Optics at surface; (240.6690) Optics at surface: Surface waves.

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## 1. Introduction

As the size of electronic transistors reach to nanoscale dimensions, this creates a significant bottleneck for the interconnect data transmission speeds within VLSI circuits. Plasmonics is seen widely seen as the next technology that will overcome this interconnect speed limitation bottleneck. Therefore, in recent years, plasmonics have become an increasingly important research area and have received a considerable amount of interest [1]. Plasmonic structures are also of interest for several other applications, such as: data storage, biosensing, nanolithography, plasmonic chips, and efficient light sources mostly due to the possibility of integrating subwavelength structures that will enable enhanced functionalities. In 2002, Lezec *et al.* [2] proposed that a subwavelength metallic aperture with periodic grooves can be used to enhance and confine light into a small spatial region via coupling to surface plasmons (SPs), which are the collective excitation of electrons at the surface of a conductor in the longitudinal direction. Since SP modes have longer wave vectors than the light waves of the same energy, electromagnetic radiation does not interact with the SP modes of a smooth metal surface [3]. However, when the metal surface surrounding the subwavelength aperture is corrugated, the incident light can couple to surface waves that mimic SPs. Since the initial reporting of enhanced and directional beaming through subwavelength apertures, this phenomenon has been intensively researched in all its theoretical and experimental aspects [4, 5, 6, 7, 8, 9, 10]. All of this conducted research concerns the coupling of the transmission to the far field. However, the transmitted EM waves confined at the output surface can be useful in some cases, such as: surface waveguiding of EM waves. In 2003, Brova-Abad *et al.* showed how the corrugation in the input side can be used to transmit selectively only two different wavelengths [11]. Recently, Gan *et al.* introduced a novel plasmonic surface wave splitter using the advantage of surface waves on the metal/air interface [12]. In the present paper, we investigated the splitting of surface Electromagnetic (EM) waves via one-dimensional metallic gratings with a sub-wavelength aperture in the microwave regime. We designed the output gratings of the structure asymmetrically such that the output surfaces at the different sides of the subwavelength aperture can support surface waves at different frequencies.

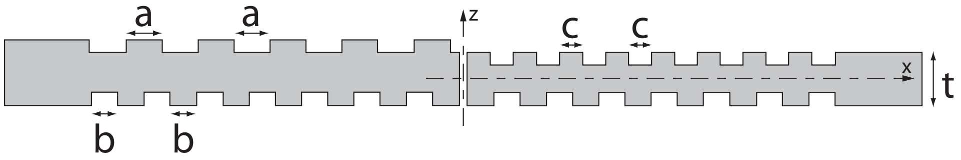
## 2. Experiment and analysis

The metallic (Al) structure, which we used in the present paper, has a subwavelength (2 mm) aperture at the center (Fig. 1). The input surface of the structure was dressed with periodic grooves. The period of the input grooves is 16 mm, which allows for the coupling of SPs by satisfying the energy and momentum conservation. While the input surface gratings allow for coupling to SP, the output surface affects the output EM waves [13].

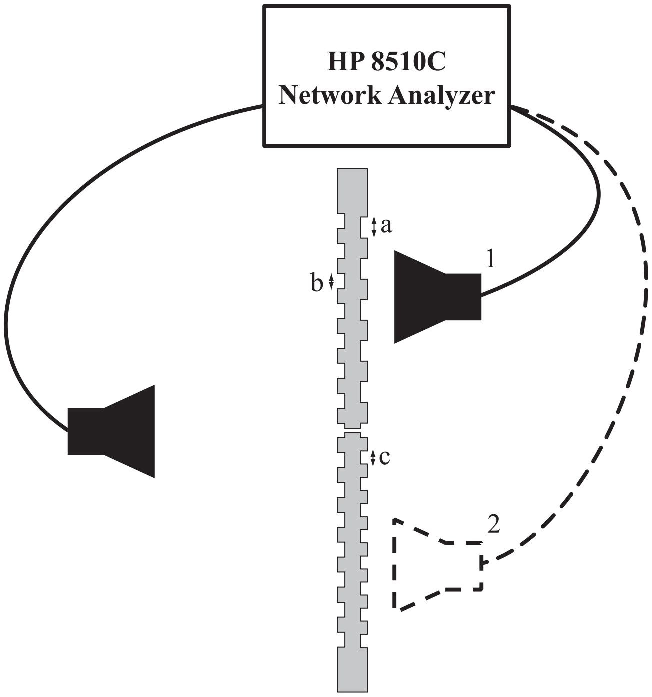
When a p-polarized EM wave is incident to the metallic surface induced surface waves, flows though the aperture and the output side of the structure. The gratings on the input side of the structure determine the wave vector of the transmitted evanescent wave. The dispersion relation of the surface modes is given as [14]:

$$\frac{\sqrt{k_x^2 - k_0^2}}{k_o^2} = \frac{a}{d}\tan(k_0 h) \qquad (1)$$

where h is the depth of the grooves, a is the groove width and d is the groove period. When the wave vector of this surface wave matches with the wave vector of the grating structure on the output of the structure; the EM waves will be trapped at the surface. Therefore, it is possible to split waves at the desired frequencies by arranging the output surface. In the present work, we optimized the output surface in order to guide the surface waves at the different sides of the aperture at different frequencies regardless of the intensity of the asymmetry, by using the commercial software (FULLWAVE), which uses the finite difference time domain (FDTD) method. However, there is a room for high transmission amplitudes. In the simulation, an electromagnetic wave with an E field that was polarized in the x direction is incident from the bottom. After the field passes through the aperture, it emits in the +z direction. The grating period of the output surface on one side of the aperture is 14 mm while the grating period on the other side is 22 mm (Fig. 1(a)).



(a)



(b)

Fig. 1. (a). The metallic (Al) grating structure has a subwavelength (2 mm) aperture at the center, in which the grating heights are 4 mm. The thickness of the structure t= 16 mm. The period of the input grooves is 16 mm (b=8 mm) and the grating period of the output surface on one side of the aperture is 22 mm (a=11 mm), while the grating period on the other side is 14 mm (c=7 mm). (b) Experimental set-up for transmission measurements.

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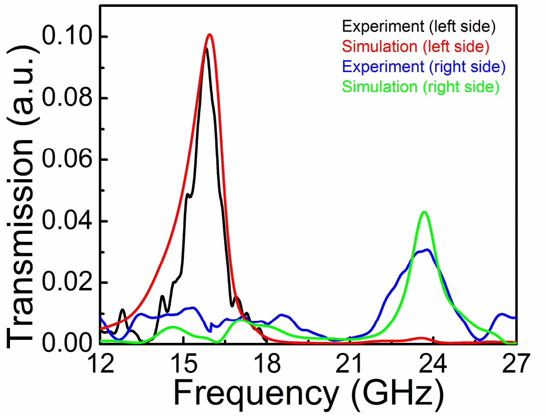

Fig. 2. The surface-waves guided through the left side (side with an output grating period of 22 mm) were at 16 GHz, while the EM waves guided through the right side of the aperture were at 24 GHz. These results are in good agreement with the FDTD calculations. The transmission amplitude measured at the left side is 1,000 times that of the right side, which is at 16 GHz. At 24 GHz, the transmission measured at the right side is 20 times that of the left side of the structure.

We measured the transmission at the different sides of the aperture. The experimental setup consists of a Hewlett Packard 8510C network analyzer and two standard-gain horn antennae in order to measure the transmission amplitude (Fig. 1(b)). Radiation is normally incident upon the sample from 15 cm by the source antenna. We measured transmission from left side and right side which are indicated as 1and 2 in the figure, respectively. The surface-waves guided through the left side (side with output grating period of 22 mm) at 16 GHz, while at 24 GHz the EM waves guided through the right side of the aperture (Fig. 2). These results are in good agreement with the FDTD calculations. The transmission amplitude as measured at the left side is 1,000 times of that at the right side at 16 GHz. At 24 GHz, the transmission measured at the right side is 20 times that of the left side of the structure. Therefore, surface waves are guided into the different sides of the aperture at different frequencies via one-dimensional metallic gratings with different groove periods on the different sides of the aperture.

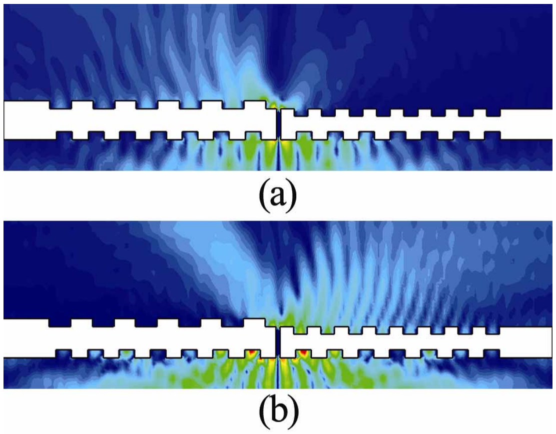

Fig. 3. The calculated E-field amplitude distributions were at (a) 16 GHz and (b) 24 GHz. The surface splitting phenomena occurs because the wave vector of the SP mode match that of the EM waves at 16 GHz for the left side of the aperture, while at 24 GHz for the right side. Red indicates the maximum and blue indicates the minimum.

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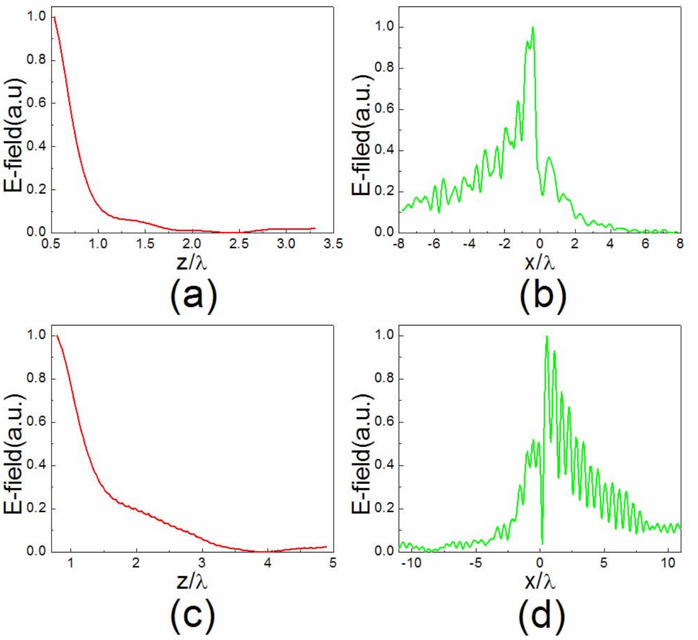

Fig. 4. The calculated (a) z and (b) x dependence of the E-field distributions were at 16 GHz and (c) z and (d) x dependence of the E-field distributions were at 24 GHz. These modes are bound to the surface and do not mostly leak into free space.

The calculated electric field distribution at 16 GHz and 24 GHz are shown in Fig. 3(a) and (b), respectively. The z and x dependence of the E-field in Fig. 4 for these frequencies show that these modes are bound to the surface and do not mostly leak into free space. Subsequently, we calculated the surface currents at 16 GHz and 24 GHz (Figs. 5(a) and 5(b)). These results show that the transmitted light was confined at the output surface. The surface splitting phenomena occurs because the wave vector of the SP mode match that of EM waves at 16 GHz for the left side of the aperture, while at 24 GHz for the right side.

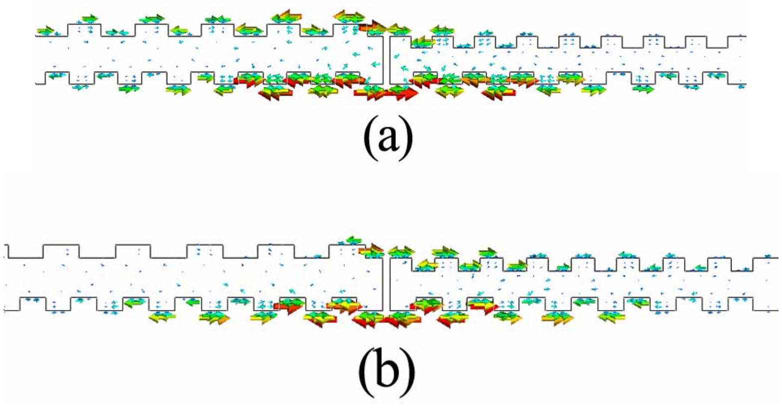

Fig. 5. The calculated surface currents were at (a). 16 GHz (Media 2) and (b). 24 GHz. (Media 1) Red indicates the maximum and blue indicates the minimum. Phase of the currents changes by 10 degrees. (GIF-video file, 616Kb, 458Kb)

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Moreover, at specific frequencies, we use two power flow probes at the top of the grooves at different sides in order to monitor the amplitude and phase of the power flow. The distance between the probes and grooves is 1 mm. Figure 6 shows the time-varied power flows at the different sides of the aperture from which we can obtain information on the amplitudes and phases. The amplitude of the power flow is quite different for the probes on the right and left sides of the aperture.

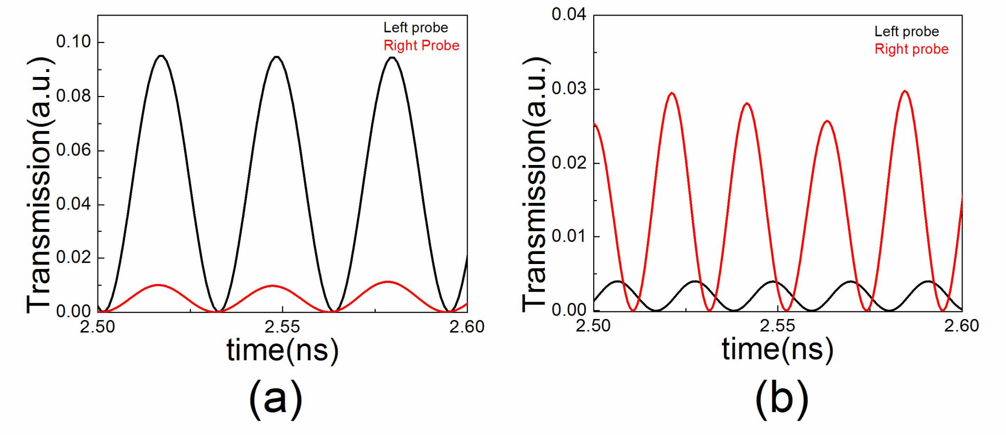

Fig. 6. The time-varied power flows at the different sides of the aperture (a) at 16 GHz and (b) 24 GHz. The amplitude of the power flow is quite different for the probes on the right and left sides of the aperture.

## 3. Conclusion

In conclusion, we investigated the splitting surface EM waves using one-dimensional metallic gratings with a subwavelength aperture at the center at microwave frequencies. We designed the output surface such that the grating periods are different on the different sides of the aperture. Therefore, the EM waves trapped at the surface guided through the right and left sides of the aperture at 16 GHz and 24 GHz, respectively. This structure can be used for several applications, such as: biosensing or interconnection for plasmonic chips.

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