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Anomalous microwave reflection from a metal surface induced by spoof surface plasmon*

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The reflection of X-band microwaves (8–12 GHz) from a metallic aluminum (Al) surface with groove grating corrugations was investigated experimentally. It was shown that the reflection of p-polarization is much less than the microwave reflected from the corresponding area of an unruled Al surface, with selective wavelength. The experimental results demonstrated that the anomalous microwave reflection is strongly associated with the excitation of spoof surface plasmons at the Al–air interface by the surface grating coupler. This near-total absence of reflected microwaves is similar to the famous Wood's anomaly in the optical regime and is of fundamental importance to the applications of spoof surface plasmons in the microwave regime.

Keywords: spoof surface plasmons, anomalous reflection, metal surface

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1. Introduction

Surface plasmons (SPs),[1] sometimes called surface plasmon polaritons, are transverse magnetic waves (TM) that propagate along the interface between two media but decay exponentially with the distance from the interface into both media. The electric field amplitude of SPs at the boundary is strongly enhanced at the resonance frequency due to free conduction carriers, leading to further enhancement of wave–matter interactions. This surface localization, which confines the electromagnetic fields to the interface, has attracted considerable attention in the last decades. Since Ebbesen *et al.*[2] first reported the extraordinary optical transmission (EOT) through nanohole arrays in an optically opaque metallic film, it has been extensively investigated in subwavelength optics and new plasmonic applications.[3–8] In addition, metallic subwavelength structures have become one of the main research branches, also in the studies of the microwave regime[9–14] and THz frequencies.[15,16] In the wavelength range of microwave frequencies, the electromagnetic surface modes are referred to as spoof surface plasmons[17,18] using language borrowed from optical technology.

As is known, metal surfaces are outstanding reflectors for incident electromagnetic waves. However, if SPs are launched in a certain wavelength region at the metal–dielectric interface, the energy of the incident electromagnetic waves will convert into that of SPs, giving rise to the reflection minimum. In this study, the influence of spoof SPs on the microwave reflection from a metallic aluminum (Al) surface was examined. The spoof SPs at the Al surface were excited by patterning the metal surface with periodic corrugated grooves, i.e., to form a surface grating coupler. Extraordinary attenuation of microwave reflection from the periodic corrugated Al surface was observed when spoof SPs are excited successfully. This grating coupling method of exciting SPs to decrease microwave reflection has also recently been employed in experiments performed with overdense plasma.[19–21] The groove gratings are clearly acting as resonators, and the experimental phenomenon is similar to the famous anomalies in diffraction from metal gratings (Wood's anomaly) in the optical regime.[22] To the best of our knowledge, we present here the first anomalous reflection spectra of

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electromagnetic waves from a metal surface in the X-band microwave region experimentally. Most SP-related experiments and simulations were performed in the optical regime, while fewer were carried out at microwave frequencies. Our experimental results are of potential use to a number of applications in the microwave frequency regime, such as spoof SP modulators, spoof SP sensors, and microwave frequency selective absorbers.

2. Physical model

For metal, the frequency-dependent dielectric constant can be expressed using the Drude model, which has the same expression as that in nonmagnetic plasmas

$$\varepsilon(\omega) = 1 - \frac{\omega_{\rm pe}^2}{\omega(\omega - {\rm i}\,\nu)}, \tag{1}$$

where $\omega_{\rm pe} = \sqrt{n_{\rm e}e^2/\varepsilon_0 m_{\rm e}}$ and ν are the plasma and collision frequencies, respectively. For metallic Al at microwave frequencies, we found that the permittivity is approximately $\varepsilon_{\rm Al} = -10^4 + 10^7\,{\rm i}$, being almost perfectly conducting.[10] Thus, the Al–air interface allows for the location of spoof SPs, whose frequency-dependent wave number is[4,23]

$$\kappa_{\rm sp} = k_0\sqrt{\frac{\varepsilon_0\varepsilon_{\rm Al}}{\varepsilon_0 + \varepsilon_{\rm Al}}}, \tag{2}$$

where ε_0 is the permittivities of air ($\varepsilon_0 = 1$), and $k_0 = \omega/c$ is the free-space wave number of the incident microwaves. Equation (2) shows that momentum mismatch exists between the conditions of free-propagating field localization and SP resonance.

Generally, for a planar metal surface, it is impossible to launch SPs by direct coupling. There are several ways to couple free-propagating electromagnetic waves into SPs along the surface, such as using a prism or patterning a periodic surface structure to make up for the wave vector mismatch. In this work, a surface-grating-coupled method was employed. The metal surface with a properly designed diffraction grating can be regarded as a one-dimensional lattice. SPs are resonantly excited when their momentum matches that of the grating and the incident microwaves of p-polarization, that is[23]

$$\kappa_{\rm sp} = k_0 \sin\theta \pm n k_{\rm g}, \tag{3}$$

where $k_{\rm g} = 2\pi/\lambda_{\rm g}$ is the Bragg reciprocal-lattice wave number of the grating structure, θ is the incident angle, and n is the coupling order that can only be an integer.

3. Experiment and discussion

Figure 1 shows the Al plate of the grating surface designed for the reflection measurement in comparison with the reference plate of a smooth surface. The two Al samples were designed for the study in X-band microwaves (8–12 GHz), and both have a surface area of 300 mm×287.5 mm. Plate A, with thickness of 10 mm and no surface corrugation, served as the reference sample for reflection measurements. Plate B, with thickness of 15 mm, is consisted of 11 sub-wavelength grooves at the incident surface. The identical rectangular grooves were all of 5 mm in depth and 12.5 mm in width, and the surface grating had a period $\lambda_{\rm g}$ of 25 mm. These geometrical parameters are designed mainly according to our previous work carried out for X-band microwave transmission and the optimization of geometrical parameters to excite SPs.[12,13]

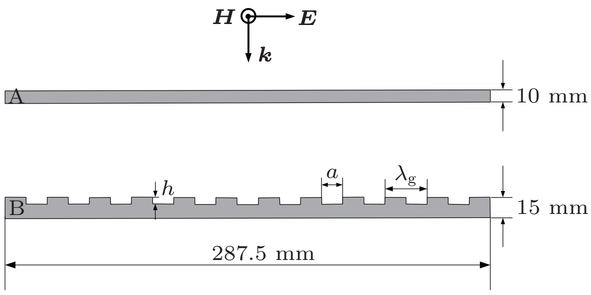

Fig. 1. Illustration of the two Al plates for the reflection measurement, with $\lambda_{\rm g} = 25$ mm, $a = 12.5$ mm, and $h = 5$ mm. A sketch of the p-polarized normal incident radiation is also shown.

In our experiments, an E8362B network analyzer and two circular microwave horn antennas were employed to measure the microwave reflection. The two identical horn antennas, each with a diameter of 110 mm, cover the X-band microwaves. Figure 2 illustrates the schematic setup of our experiments. As shown in Fig. 2, one antenna was used to generate the incident microwaves while the other one was used to receive the reflection signal. In this work, experiments were all performed for normal incident radiations ($\theta = 0$). However, it is necessary to note that the two antennas we used were manufactured for transmission measurement. They both had a high-reflectivity point at the interior waveguide transfer position, so the method of using only one antenna to measure the reflection by recording S_{11} was not available. Instead, we employed two parallel antennas to measure the reflection by recording S_{21} or S_{12}, as displayed in Fig. 2. For the microwave network analyzer measurement, S_{11} is the reflection recorded by the radiation antenna itself, while S_{21} (or S_{12}) means the signal received by the other antenna. Moreover, both antennas could also be manipulated to support p-polarized or s-polarized microwaves if necessary. For p-polarization (TM waves), polarization for which excitation of spoof SPs occur, $\boldsymbol{B}$ vector is perpendicular to the wave vector $\boldsymbol{k}_{\rm g}$ of the surface grating. Correspondingly, the $\boldsymbol{E}$ field is perpendicular to $\boldsymbol{k}_{\rm g}$ for s-polarization (TE waves).

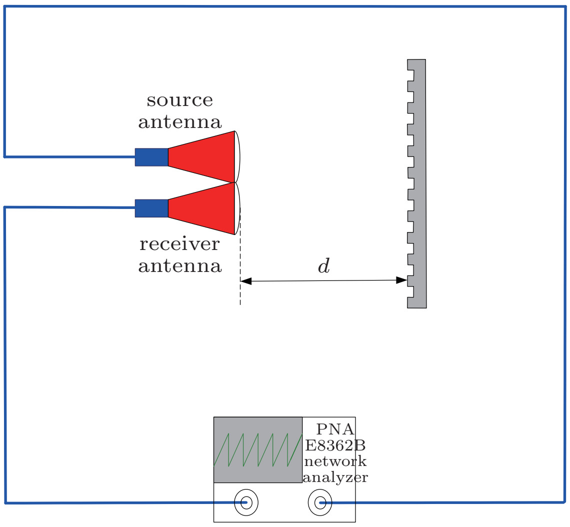

Fig. 2. (colour online) Experimental scheme for investigating the influence of spoof SPs on microwave reflection.

In this study, through-response calibration of an E8362B network analyzer was adopted, and plate A without surface corrugation was modeled as the through standard. Figure 3 shows the p-polarized microwave reflection spectra from different metal surfaces, and the reflection signal from microwave absorbing material is also illustrated for comparison. The absorbing material, which attenuates microwaves enormously, has a thickness of 100 mm and an area of 450 mm×450 mm. In Fig. 3, the distance between the antenna and the measured surface was $d = 300$ mm, and the calibration signal is the reflection spectra of plate A (dashed line). We can see clearly that the surface grating structure tremendously influences the reflection spectra of plate B (bold solid line). In the frequency range of 10–11 GHz, the reflected microwaves from the grating surface attenuate more than 10 dB. A deep minimum reaches more than 30 dB at $f_{\min} \approx 10.5$ GHz ($\lambda_{\min} \approx 28.57$ mm), being almost total absorption of radiation by th emicrowave absorbing material (thin solid line). Note that the period of the metallic surface grating is $\lambda_{\rm g} = 25$ mm, and the reflection minimum of plate B appears at $\lambda_{\min} \sim \lambda_{\rm g}$. This strongly indicates that the anomalous microwave reflection is associated with the excitation of spoof SPs at the metallic surface. The reflection minimum shift toward a longer wavelength ($\lambda_{\min} = 1.14\lambda_{\rm g}$, $\Delta\lambda = \lambda_{\min} - \lambda_{\rm g} \simeq 0.14\lambda_{\rm g}$) is often regarded as redshift, which has been reported and analyzed in many works.[3,6,12,24] For the Al–air interface with normal p-polarized incidence, $\kappa_{\rm sp} = nk_{\rm g}$ would be obtained from Eq. (3), and $n = \pm 1$ would give rise to $\kappa_{\rm sp} = k_{\rm g}$, i.e., $\lambda_{\rm sp} = \lambda_{\rm g}$. In addition, if we substitute the permittivity of Al ($\varepsilon_{\rm Al} = -10^4 + 10^7\,{\rm i}$ at microwave frequencies) and air ($\varepsilon_0 = 1$) into Eq. (2) simultaneously, we will obtain $\kappa^{\rm r}_{\rm sp} \approx k_0$, which means that spoof SPs can physically exist at Al–air interface in the microwave region.

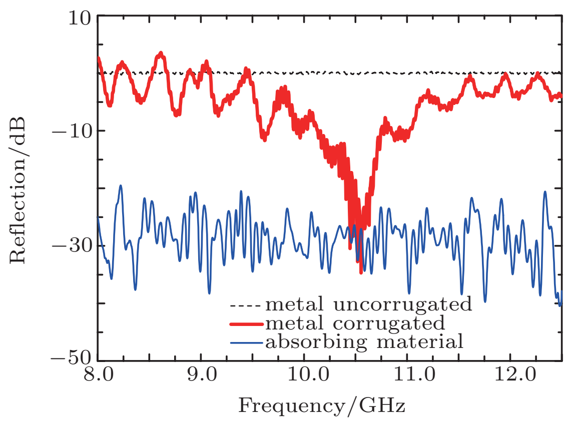

Fig. 3. (colour online) The frequency spectra of microwave reflection from different samples ($d = 300$ mm). For metal with a grating surface (plate B), the incident microwaves are p-polarized.

In order to better understand the underlying physics of the anomalous microwave reflection from the corrugated metal surface at $\lambda_{\min} \approx 28.57$ mm, the corresponding reflection spectra of plate B at s-polarization were also found. Figure 4 illustrates the s-polarized reflection spectra compared with that at p-polarization, which was also calibrated by plate A (dashed line). The measured surface was located 300 mm from the antennas, as in the experiments whose results are shown in Fig. 3. Comparison shows that the anomalous microwave reflection at p-polarization does not appear in the s-polarized case. As a whole, the s-polarized microwave reflection remains as high as that from a smooth metallic surface in the microwave band investigated. This polarization anisotropy also strongly suggests that spoof SPs are involved in the corrugated surface achieving extraordinary attenuation of microwave reflection at p-polarization.

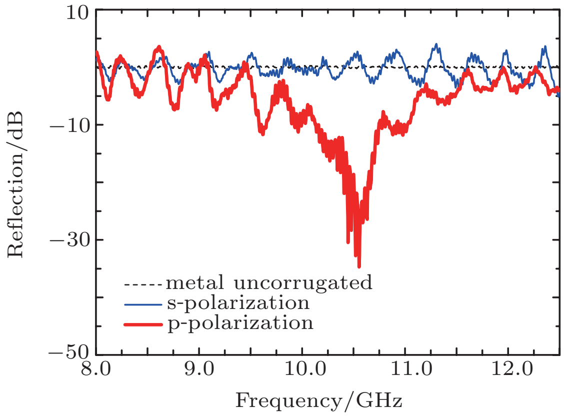

Fig. 4. (colour online) The reflection spectra of plate B at s-polarization compared with that at p-polarization, ($d = 300$ mm).

4. Conclusion

In summary, we have experimentally investigated the microwave reflection from a metallic aluminum surface with groove grating corrugations in the X-band microwave region. Extraordinary attenuation of microwave reflection from the Al surface can be achieved when the surface structures are properly designed, i.e., near total absence of reflected microwaves with selective wavelength. By combining the experimental results with the theory of SPs, it was found that the anomalous microwave reflection results from the excitation of spoof SPs at the Al–air interface. The spoof SPs were resonantly excited with the periodic grating grooves corrugated in the metal surface to make up for the wave vector mismatch (p-polarization). This phenomenon is similar to Wood's anomaly in the optical regime. Such a possibility of remarkably attenuating microwave reflection with selective wavelength is very attractive for a number of important applications based on this phenomenon. We suggest that this type of surface has potential to act as a microwave frequency selective absorber, or with tailored geometrical parameters, to confine or channel microwave power flow across a flat surface.

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