SURFACE PLASMON THZ RESONATORS FOR SECURITY APPLICATIONS

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ABSTRACT. This paper investigates the use of surface plasmonic effect in slit resonators for sensing and imaging in the terahertz regime. The transmittance of electromagnetic (EM) waves through a narrow aperture becomes negligible when the aperture size becomes much smaller than the wavelength. However, with the resonant excitation of charge density waves in the metal/air interface, called the surface plasmons, an extraordinary transmittance has been observed through such apertures. Using slit resonators of 50 to 100 μm width, we have demonstrated enhanced transmission of THz radiation through the slits. The ability to concentrate the EM radiation through a sub-wavelength aperture bodes well for detection of chemical or biological materials with high sensitivity or for super-resolution imaging of materials for NDE. We present results of using a slit resonator for chemical detection and for super-resolution imaging of materials for NDE.

Keywords: Terahertz, Microwave, Surface Plasmon, Electromagnetic Waves, Chemical Detection, Biological Detection

INTRODUCTION

The subject of surface plasmons is an exciting area of research with applications in sensors, nanomaterials, and nanoscale electronics [1]. Surface plasmons are charge density waves originating from the collective excitation of electrons at a metal/dielectric interface; electromagnetic waves at visible and ultraviolet frequencies have been used to resonantly excite and manipulate the surface plasmonic interaction with a dielectric medium. The ability to control and concentrate electromagnetic energy in length scales much smaller than the excitation wavelength opens up great opportunities for sensing and imaging. The fact that the resonance coupling behavior is ultra sensitive to changes in the dielectric property of the medium forms the basis for many types of sensor development. Surface plasmon resonance (SPR) sensors are actively pursued mainly in the optical region using visible or ultraviolet light [2] because the conditions for surface plasmon propagation are readily met in the optical region. Highly sensitive chemical and biomolecular sensors have been developed using these methods at optical frequencies.

SP work is also underway in other parts of the electromagnetic spectrum including microwaves. Enhanced microwave resonance transmission through a sub-wavelength slit in a metal surface has been known, called Wood's anomaly, since 1902, but only recently has it been elucidated that the surface plasmons contribute to the extra-ordinary transmission properties [3-5]. This paper examines the use of SP-based slit resonators for millimeter-wave/terahertz sensing and imaging in the 200-300 GHz range.

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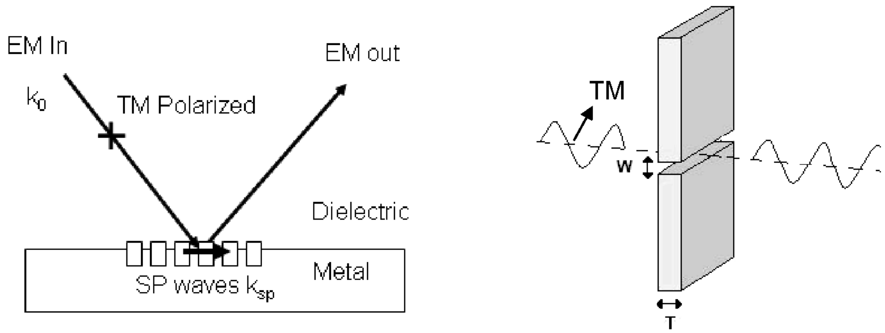


(a) (b)

FIGURE 1. Excitation of surface plasmon wave using (a) Grating structure and (b) Slit structure.

SURFACE PLASMON RESONATOR

To couple the EM waves to surface plasmons, the incident wave must be TM polarized and the free space wave vector k_0 must match the SP wave k_{sp}. Such conditions are generally fulfilled in metal air system with grating or slit structures (Fig. 1).

We investigated a single sub-wavelength slit as in Fig. 1(b) for its transmission properties in the mm-wave regime. Figure 2 gives the experimental setup in which a single slit structure was formed by inserting layers of Mylar film between the ends of two polished aluminum plates. The slit structure is inserted into a mm-wave absorbing pad (Eccosorb) so that the incident mm-wave beam is precluded from transmitting around the plates. The mm-wave source is a backward wave oscillator, tunable over 220-370 GHz and capable of providing ~30 mW of power. A hot electron bolometer is used to detect the mm-wave radiation through the slit. A 15-cm lens is used on the transmitter side to focus the beam on the slit with a waist size of 7 cm and another lens of identical type is used to focus the rather divergent radiation emanating from the slit on to the bolometer.

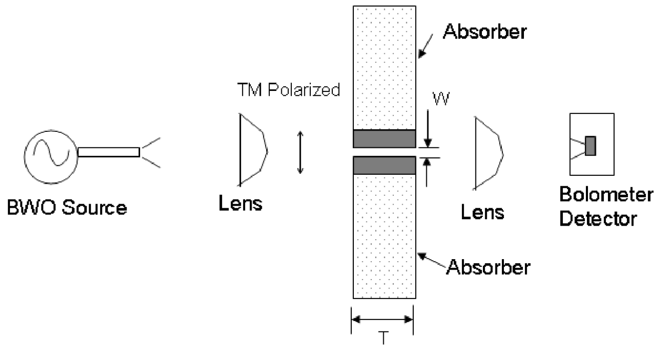
When the slit width $w \ll \lambda$, the incident wavelength, an enhanced transmission occurs for TM polarized waves due to surface plasmon coupling in the slit. Based on previous studies [2,6], the enhanced transmission follows Fabry-Perot-like resonance in which the slit acts as an open-ended cavity. The Fabry-Perot (F-P) resonance is satisfied when

$$\lambda_{FP} = \frac{2nT}{N}, \tag{1}$$

where λ_{FP} is F-P resonance wavelength, c the speed of light, n the refractive index of the medium in the gap, N the mode number and T the depth of the slit. For narrow slit widths, however, there is a shift (decrease) in resonance frequency from the ideal F-P resonance depending on the slit width. The shift in wavelength is given by:

$$\frac{\lambda_{shift}}{\lambda_{FP}} = \frac{2(w/T)[\ln(\pi w/\lambda_{FP}) - 1.5]}{2(w/T)[\ln(\pi w/\lambda_{FP}) - 0.5] - \pi}. \tag{2}$$

(a)



(b)

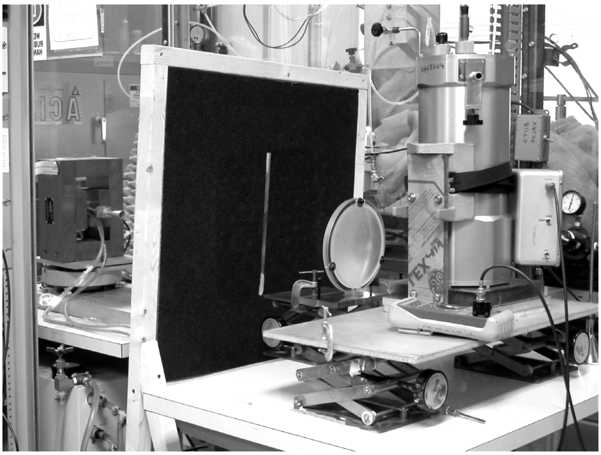


FIGURE 2. Millimeter wave experimental setup (a) schematic diagram and (b) photograph showing transmitter, slit structure, and bolometer.

Using w= 50 μm and T= 5 cm, Fig. 3 shows the simulated F-P resonance lines [2] and the corresponding measured transmission resonance signal in the 230-290 GHz interval. The simulation and measurement did not match well; however, an enhanced transmission was clearly observed for the TM-polarized wave; the disagreement may be attributed to the unevenness of the cavity widths over the depth.

SENSING

The sensitivity of detection to chemical or biological materials with SP resonators can be high because they provide strong concentrated electric field in the dielectric sensing volume. High selectivity of detection can also be obtained by exciting the SP-mediated cavity modes at the resonance frequencies of the sample. With a swept frequency source such as a backward-wave oscillator, a range of FP cavity modes can be excited in the slit; the spectral characteristics of the sample may be derived from the FP responses with and without the sample.

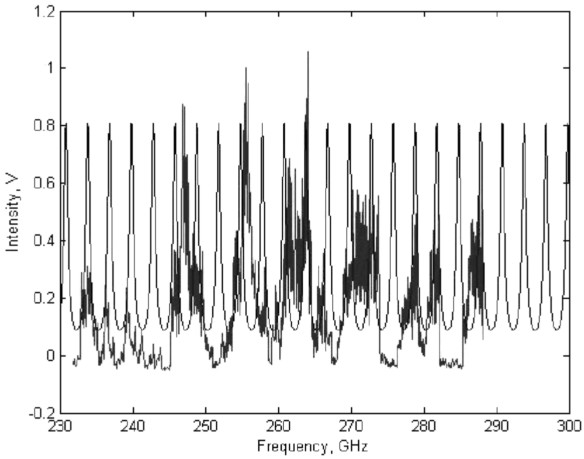


FIGURE 3. Simulated and measured response of surface plasmon resonator.

The SP resonator may be used for detection of chemical or biological materials by building a sampling system around the slit; when the sample is near or within the slit, the SP resonance is affected by the change in dielectric property of the sample. To test the sensitivity to chemicals, a few drops of liquid ethanol were sprayed on the back of the slit, which resulted in very near extinction of the signal (Fig. 4). As the liquid ethanol evaporated with time, the signal began to build up as shown by other traces in between the smallest and the tallest amplitudes. While further work is needed in comparing theory and experiment and testing the absorption spectra of chemicals inside and around the surface of a slit structure, the initial results in Fig. 4 indicate the potential of the technique for sensitive detection of chemicals and other materials in a sub-wavelength structure.

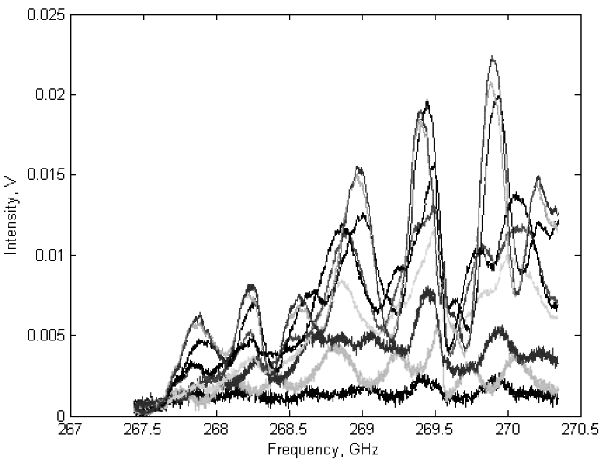


FIGURE 4. Attenuation of the transmitted signal through slit for droplets of ethanol sprayed on the slit; the signal builds up from near extinction to the original level as the ethanol evaporates.

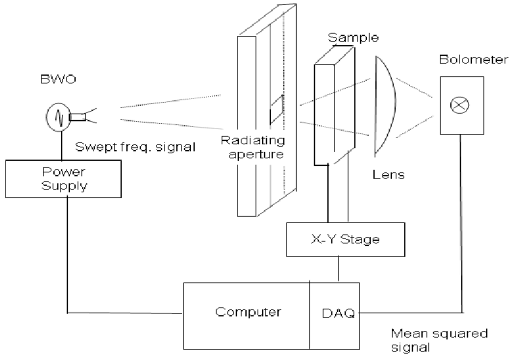
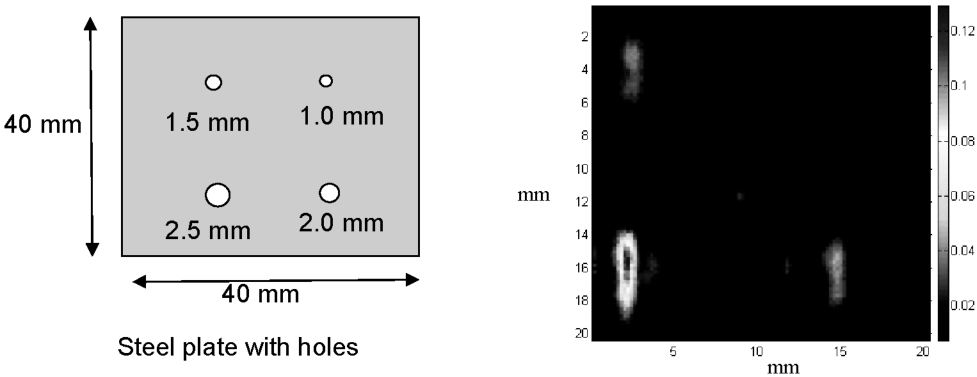


FIGURE 5. Surface plasmon-based super-resolution imaging system.



(a) (b)

FIGURE 6. Drawing of steel plate with holes (a) and its millimeter wave through transmitted image (b); the x and y dimensions are in mm.

IMAGING

Millimeter-wave imaging is an emerging NDE technique for noncontact mapping of defects in nonmetallic materials [7,8]. The image resolution of such electromagnetic techniques is governed by the size of their wavelength because of diffraction limits. Recently, near-field microscopy techniques have come to fore which allow image resolution much less than the wavelength [9]. Because of the use of evanescent fields, only near surface properties are imaged with these techniques. In this paper, we describe a method of improving the resolution of free space techniques by creating surface plasmon (SP) based sub-wavelength radiating apertures.

The ability to concentrate the EM radiation through a sub-wavelength aperture can be exploited for high-resolution imaging. We created a 100 μm x 1.8 mm aperture by creating a100μm slit with spacers and blocking the back side with an aluminum foil with an opening of 1.8 mm. The sample to be imaged is scanned along the x-y direction with a

2-axis translation stage (Fig. 5). Because the radiation exiting the aperture diffracts highly and the beam widens as a function of distance from the slit, the test samples were kept very close to the slit. For thicker samples, the emergent beam can be made more directed by using corrugations around the slit on the back surface [4]. Figure 6 is a through-transmitted image of a steel plate with four holes of diameter: 1.5, 1.0, 2.0, and 2.5 mm, clockwise from the top left. The circular holes look rectangular in the image because of the 1.8 mm long aperture in the vertical direction. The capability to image materials with image resolution under 100 μm is evident from these images.

Next, we imaged pharmaceutical drugs for the purpose of mapping their density distribution. These are generally coated on the outside whose thickness varies depending on the required release rate of the drug during intestinal transport. Figure 7 shows the mm-wave images of three tablets: Tylenol, Aspirin, and Vitamin C (clockwise from the top). The coating thickness appears nonuniform across the tablets (assuming uniform distribution of the drug within) with higher thickness at the edges, owing likely to the concave nature of the tablets. Such imaging could be useful for drug quality monitoring and counterfeit detection. In another test, we imaged a TUMS tablet with the label inscribed on its backside (Fig. 8). The inscription of the lettering on the tablet appears to be visible in the image.

These results indicate the potential of creating a sub-wavelength radiating aperture and using it to image non-metallic materials such as pharmaceutical tablets and composite materials with millimeter waves for nondestructive evaluation. The traditional diffraction-limited image resolution barrier may be broken using surface plasmonic structures. The single slit structure may be improved with corrugated grooves on both sides of the slit with further enhancement in transmission and narrow beams [4].

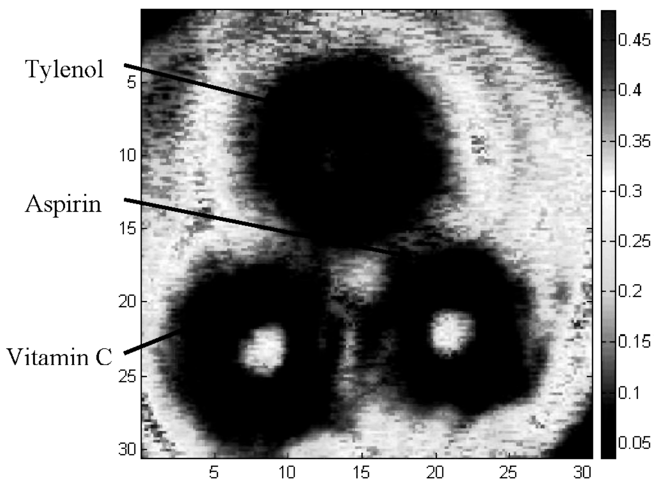


FIGURE 7. Millimeter wave transmitted images of tablets.

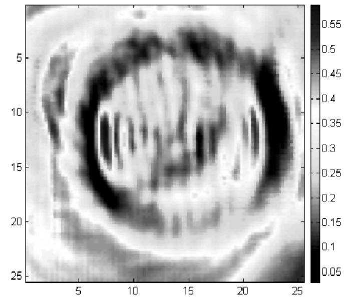


FIGURE 8. Image of TUMS tablet with the label on the backside.

CONCLUSION

We investigated the use of surface plasmonic effect in the THz regime for security applications. A subwavelength single-slit SP resonator was built with two aluminum plates with a separation of 50 μm. Due to SP coupling of EM waves, enhanced transmission of THz signal in the 230-290 GHz range was observed through the slit. Initial testing with ethanol liquid droplets on the slit indicates very good sensitivity for chemical detection. The ability to concentrate the EM radiation through a sub-wavelength aperture bodes well for super-resolution imaging. We created a 100 μm x 1.8 mm aperture using a slit resonator made of aluminum plates. Through-transmitted images at wavelengths of ~1.1 mm (269 GHz) were created by scanning the samples across the aperture. We have demonstrated super-resolution (<0.1 mm) imaging by scanning a metal plate with 1 to 2.5 mm-size holes. The utility of the technique for NDE was examined by imaging pharmaceutical tablets where the coating thickness is of interest.

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