A Terahertz Plasmonic Metamaterial Structure for Near-Field Sensing Applications

Amir Arbabi, Arash Rohani, Daryoosh Saeedkia, and Safieddin Safavi-Naeini
Electrical and Computer Engineering Department, University of Waterloo, Waterloo, Ontario, Canada

***Abstract*—A highly sensitive terahertz surface wave sensor structure is proposed for near field spectroscopy and sensing applications. A periodically patterned metallic structure is used to guide plasmonic surface waves at THz frequencies. The quasi-optical continuous wave (CW) terahertz radiation is coupled to this structure using the Otto attenuated total reflection (ATR) configuration. It is shown that terahertz surface waves can be supported by the proposed structure. The sensitivity of the device is discussed.**

I. INTRODUCTION

SURFACE plasmon polaritons are electromagnetic surface waves coupled to electron plasma oscillation of metals at a metal-dielectric interface. At optical frequencies, these modes are of great interest because of their high confinement to the interface. At these frequencies, surface plasmon resonance sensors are known to be highly sensitive [1]. Many important chemical and biological molecules have their vibrational and rotational resonance frequencies in the THz range that makes the THz sensing as one of the most important applications in THz technology. Unlike optical surface plasmons, THz surface plasmons are not highly confined to the metal-dielectric interface due to large negative real part of the metal permittivity at THz frequencies. However, by engineering the design parameters of a periodic metallic structure (plasmonic metamaterial) small negative (absolute value) dielectric constants can be obtained. Recently, guiding of THz pulsed waves on a periodic metallic structure made of an array of holes has been reported [2].

In this paper, a novel metallic plasmonic metamaterial structure for THz frequencies is proposed and ATR technique is used to excite CW THz surface plasmonic waves on the proposed structure. The dispersion curves for the excited plasmonic modes are calculated and the sensitivity of the proposed device for THz sensing and spectroscopy application is discussed.

II. PROPOSED STRUCTURE

Fig. 1(a) shows the proposed structure which is composed of an array of square metallic columns made on a metallic substrate. This periodic structure can support surface waves. The magnitude of the electric field for the first guided surface mode is shown in Fig. 1(b). The simulation is done using the 3-D electromagnetic simulator software Ansoft HFSS. For the simulation purpose, the columns and the substrate are assumed to be made of perfect electric conductor, which is a good approximation for most metals in the terahertz region. Periodic boundary condition is used on sidewalls and the structure is terminated with a perfectly matched layer (PML) in the vertical direction. The PML is placed $300\,\mu m$ above the columns to eliminate its effects on the field distribution. As it can be seen from Fig. 1(b), the field is highly confined to the surface and is highly enhanced at the edges and the corners of the metallic columns. Due to the fact that guided surface modes' propagation constants are larger than the free space wave number (k_0), they can be excited in an ATR configuration. Figure 1(c) shows such a configuration known as Otto configuration. For an incident CW terahertz beam, the power of the reflected beam shows a minimum at the coupling angle θ_m for which the phase matching condition ($n_p k_0 \sin\theta_m = \beta$) is satisfied, where n_p is the refractive index of the prism and β is the propagation constant of the guided surface mode. The coupling angle θ_m is extremely sensitive to the refractive index of the medium between the prism and the metal surface. This configuration can be used as a sensor to measure the dielectric constant of the sample material placed between prism and the metallic surface. For this structure, a sensitivity parameter can be defined as $S = d\theta_m / dn_{sample}$. From the matching condition we have:

$$\sin\theta_m = \frac{\beta}{n_p k_0} \quad (1)$$

and by taking derivative with respect to sample refractive index:

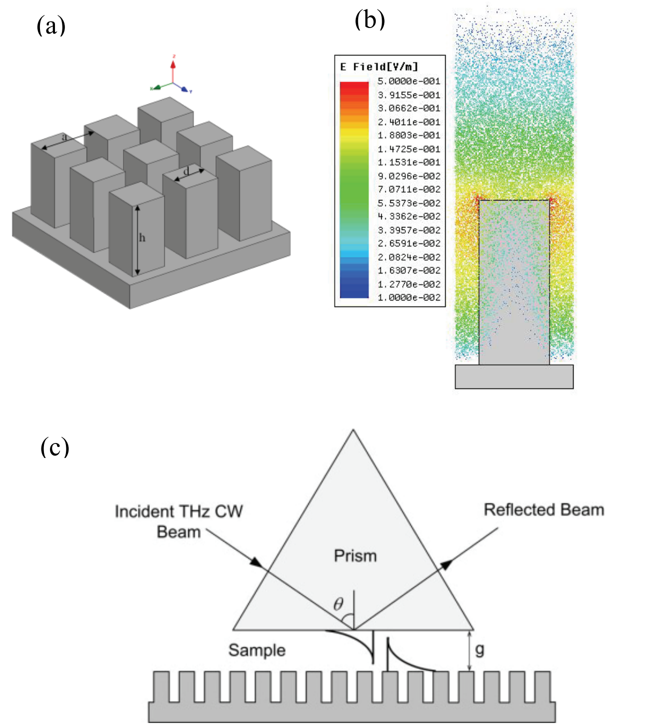

Fig. 1 (a) Proposed metallic plasmonic metamaterial structure. $a = 50\,\mu m$, $d = 30 \mu m$, and $h = 60\,\mu m$. (b) Magnitude of the electric field of the first surface wave mode at 870 GHz. (c) Excitation configuration.

978-1-4244-2120-6/08/$25.00 ©IEEE.

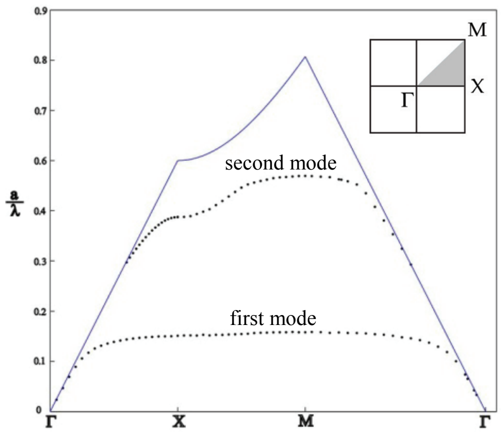

Fig. 2 The band diagram for the first two surface wave modes of the structure shown in the fig. 1

$$S = \frac{d\theta_m}{dn_{sample}} = \frac{1}{n_p k_0 \cos\theta_m}\frac{d\beta}{dn_{sample}} \qquad (2)$$

Assuming that the sample fills the space between and above the columns (in practice it is sufficient to only fill the regions near the surface where the field is strong), the propagation constant β will be a function of wave number in the sample medium ($k_{sample} = \omega n_{sample}\sqrt{\mu_0\epsilon_0}$) and therefore:

$$\frac{d\beta}{dn_{sample}} = \frac{\omega}{n_{sample}}\frac{d\beta}{d\omega} = \frac{\omega}{n_{sample}}\tau \qquad (3)$$

where τ is the group delay of the surface mode. From (2) and (3):

$$S = \frac{c}{n_p n_{sample}\cos\theta_m}\tau \qquad (4)$$

where c is the speed of light in vacuum. From (4) it can be observed that sensitivity is proportional to the group delay of the excited surface mode. In other words, the sensitivity is proportional to the time interval over which the field and the sample interact. Therefore, for maximum sensitivity, the operation frequency should be set in the flat part of the dispersion curve (Fig. 2), where the group delay is maximum and the group velocity is close to zero. Fig. 2 shows the band diagram for the first two surface wave modes on the proposed structure which have been calculated using eigenmode solver of the HFSS with the previously mentioned boundary conditions. As it can be seen from band diagram in Fig. 2, the dispersion curve for the first surface mode becomes flat near the point X. The gap width g (Fig. 3) between the prism and the metal surface should be adjusted carefully to achieve an efficient coupling. From simulation, the optimum value is found to be $g = 100\,\mu m$ for $n_p = 3.41$ (silicon prism). The coupling angle and the sensitivity parameter are found to be $\theta_m = 34°$ and $S = 240°$ at the frequency of 870 GHz. With 0.1 degrees accuracy in the measurement of θ_m, it is possible to sense a change as small as 10^{-4} in the refractive index of the sample under test.

III. Fabrication

Figure 3(a) shows the fabricated structure. An area of $2cm \times 4cm$ is patterned using Deep Reactive-Ion Etching (DRIE) of

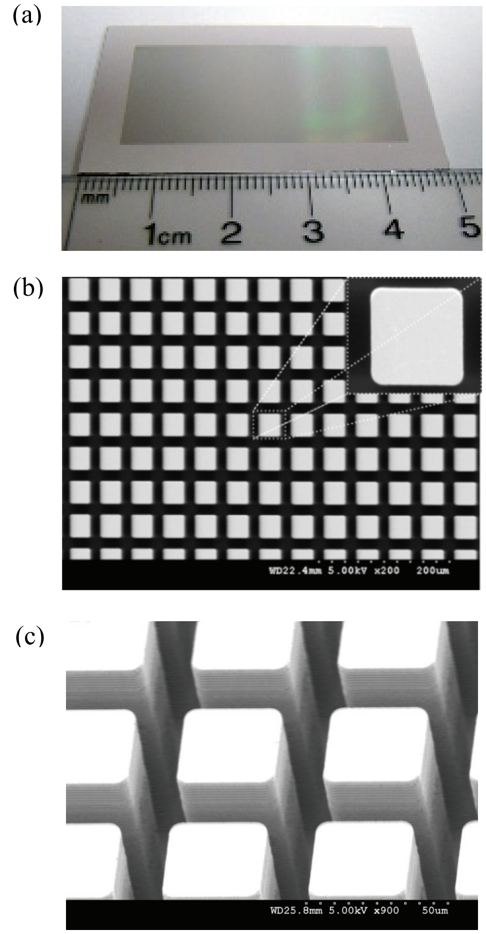

Fig. 3 (a) Fabricated surface. (b) and (c) SEM images of the proposed plasmonic metamaterial.

silicon. After etching, a 2 μm thick layer of silver is sputtered on the patterned silicon. Scanning electron microscope (SEM) images of this structure are shown in Fig. 3(b) and (c). Test and characterization of the fabricated device is under way.

IV. Conclusion

A periodic array of metallic columns on a metallic substrate that constitute a plasmonic metamaterial structure and can support plasmonic surface waves at terahertz frequencies is proposed. It has been shown that highly sensitive THz sensors can be realized using this structure.

V. Acknowledgment

This research work was supported by National Science and Engineering Research Council (NSERC) of Canada, Ontario Centers of Excellence (OCE), Research in Motion (RIM), and T-Ray Science Inc.

References

[1] J. Homola, S. S. Yee, and G. Gauglitz, “Surface plasmon resonance sensors: review,” *Sensors and Actuators B*, vol. 54 , no. 1-2 , pp. 3–15, Jan. 1999.

[2] C. R. Williams et al., “Highly confined guiding of terahertz surface plasmon polaritons on structured metal surfaces,” *Nature Photonics*, vol. 2, no. 3, pp.175–179, March 2008.

978-1-4244-2120-6/08/$25.00 ©IEEE.