Terahertz plasmonic waveguides based on a microstructure of metal rod array

Borwen You[1] , Wen-Jie Cheng[2], Ja-Yu Lu[2], Tze-An Liu[3] and Toshiaki Hattori[1]
[1]Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan
[2]Department of Photonics, National Cheng-Kung University, Tainan 70101, Taiwan
[3]Center for Measurement Standards, Industrial Technology Research Institute, Hsinchu 30011, Taiwan

***Abstract*—Metal rod array (MRA) are presented as the microstructured cladding of a rectangle channel waveguide to guide terahertz (THz) waves. The microstructure cladding is critical to modify the waveguide loss, dispersion, resonance, and pass-band. THz-field resonance and the corresponding modal field are taken as examples to express that the MRA period can be tailored for engineering the waveguide. MRA is agreed as a plasmonic metalmaterial, possessing spoof plasma frequency and dependent on the MRA geometry. The case of THz-field resonance inside the waveguide channel is significant to mimic "plasmonic resonance" in THz region that does not appear in natural metals.**

I. INTRODUCTION

Surface plasmon resonance (SPR) is the collective oscillation of electrons at metal-dielectric interfaces that are stimulated by electromagnetic waves. The resonance phenomenon occurs when the frequency of a photon matches the natural frequency of surface electrons, oscillating against the restoring force of positive nuclei. Surface plasmons have been used to enhance the surface sensitivity of several spectroscopic measurements including fluorescence, Raman scattering, and second harmonic generation [1, 2]. SPR schemes are thus agreed to detect molecular adsorption, such as polymers, DNA or proteins, etc. However, the photo-excitation frequency of SPR is usually in the visible or UV bands, which cannot provide any information of intermolecular interaction with the photons. To obtain the photonic response of the inter-molecular force, such high photon energy in the visible/UV light is not suitable. The corresponding photon energy to probe intermolecular force is considerably low and down to about several millivolts. This is corresponded to the spectral range of THz electromagnetic waves (1~ 10THz). The application and fundamental to optically detect the intermolecular force are urgently required due to the sensing instrument and methodologies are not well developed yet. To mimic SPR in THz-frequency domain, we apply the well-known plasmonic microstructure, MRA, to design a plasmonic channel waveguide to generate THz-field resonance that is correlated to the plasmonic MRA geometry.

II. CONFIGURATION

Figure 1 shows the optical configuration to couple THz-waves into a MRA structure, where the parallel metal plates are integrated for optimized mode matching in the X-axis. The electric-field oscillation of THz-waves is parallel to the rod-axis. The MRA structure is constructed by a 160μm-diameter and 1mm-long rod with periodical arrangement in the Y-Z plane. The rod is made of a polymer material and its surface is coated by 100nm-thick aluminum thin film. For a complete rectangle array, the air-gap space is the same in the X- and Z-axes. In the presentation, two lines of the rod along Z-axis are removed becoming a channel structure, where the rods are expressed as dot-line shapes in Fig. 1. The MRA structure is thus considered as the cladding of the channel waveguide.

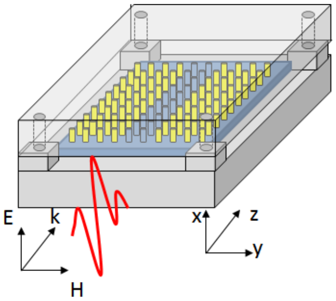

Fig.1 Waveguide configuration based on a microstructure of metal rod array.

III. TRANSMISSION SPECTRUM

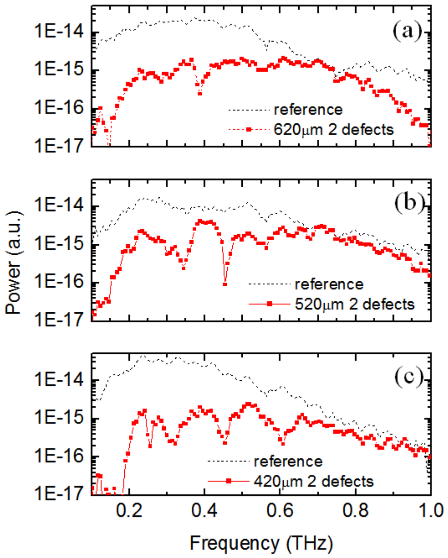

Fig. 2 Transmission spectra of MRA channel waveguide for different MRA period, (a) 620μm, (b) 520μm, (c) 420μm.

When a THz pulse is coupled and propagated along the hollow-core channel, Z-axis, there are obvious spectral dips shown in the transmission spectrum in Figs. 2(a) ~ (c). The power loss at the spectral dips is resulted from the resonance effect at the hollow-core space, correlating to the channel width. There are two line defects of the rod for the three MRA periods. The hollow-core widths are 1.24mm, 1.04mm and 0.84mm, respectively, for 620μm-, 520μm-, 420μm-MRA periods. We consider the spectral dips in the frequency range of 0.3 ~ 0.6 THz, and observe the spectral range between two dips. 520μm- and 420μm-MRAs have spectral range of dip, respectively, about 100GHz and 150GHz. It satisfies the Fabry–Pérot interference condition for the resonance mode. The resonance frequency can be considered as the equation, $\Delta\nu_m = (mC) / (2nL \cdot \cos\theta)$, where m, C, n, L, θ, are respectively the resonance mode number, light speed in vacuum, channel width, and incident angle at the core-cladding interface. The small channel width performing the large spectral dip range is hence reasonable for comparing 520μm- and 420μm-MRAs in Fig. 2.

IV. WAVEGUIDE RESONANCE FIELD

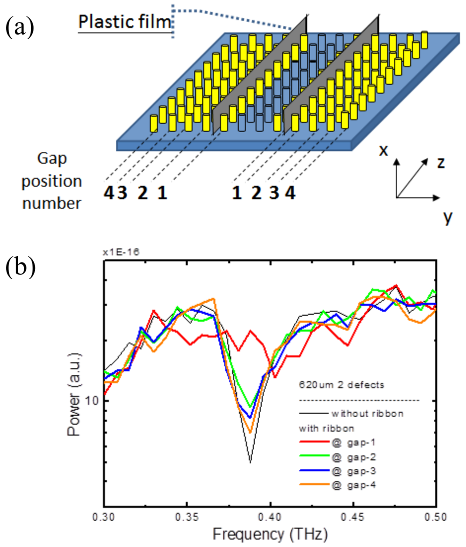

Fig. 3 (a) Waveguide configuration to probe the cross field distribution in the microstructured cladding. (b) Coupled power performance for the 620μm-channel waveguide.

The channel walls constructed by MRA microstructure make THz-field resonant inside the hollow core because this MRA structure has high reflection properties for the THz-frequency lower than the spoof plasma frequency of the MRA. The evanescent fields/waves aside the hollow core channel or inside the MRA cladding can be observed for the corresponding channel waveguide modes. We try to integrate two PVC-plastic slabs in symmetry along Y-axis at the air-gap positions. The slab's thickness is about 200μm and the gap positions are shown in Fig. 3 (a). The gap-1 is closed to the channel and, and the gap-4 is far away the channel. We take the 620μm-MRA waveguide as an example to observe the power variation at the resonance frequency when the PVC slabs are symmetrically put at different gaps of the MRA. As shown in Fig. 3(b), the transmitted power is almost coupled out when the two PVC slabs are put at gap-1. Oppositely the transmitted power approaches the blank condition (without integrating PVC slabs) while the slabs are put at gap-4, which is far away the hollow core. Figures 4(a) and 4(b) show the measured results of the cross power distribution in one side of the MRA cladding, respectively, for the periods of 420μm and 520μm. There is obviously THz-wave power leaked outside the hollow core and coupled out by the PVC slabs. The THz waves in Fig. 4 are the resonance waves as shown in Fig. 2, and this power distribution corresponds to the evanescent waves. For the 420μm-Λ waveguide, the resonance frequencies are 0.329THz, 0.453THz and 0.600THz. The evanescent wave of high-frequency resonance is confined to the hollow core, and, oppositely, that is extended for the low frequency resonance. For the 520μm-Λ waveguide, the resonance frequencies are 0.351THz and 0.453THz. The evanescent waves are much extended, comparing to those of the 420μm-Λ MRA. For example, the decay length of 0.453THz resonance at the 420μm period is about 0.49mm, and it is extended to 0.55mm for the 520μm MRA period. In other words, the cladding composed by short period MRA makes strong field confinement when THz-waves are propagated along the hollow core space.

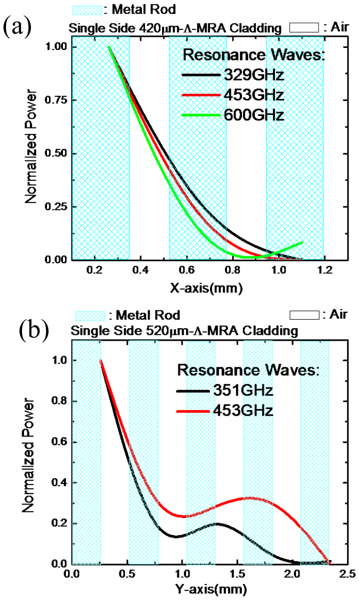

Fig. 4 The power distribution of the evanescent waves inside the (a) 420μm- and (b) 520μm-period MRA claddings.

V. SUMMARY

THz-wave resonance is demonstrated by a microstructure of MRA, composing the cladding of a rectangle hollow-core waveguide. Both the resonance frequency and the local field confinement at the metal-dielectric interface are approved in the presentation to be engineered simply by the MRA period based on the same metal rod, whose diameter and length are, respectively, 0.16mm and 1mm.

REFERENCES

[1] A. Abbas, M. J. Linman, Q. Cheng, "New trends in instrumental design for surface plasmon resonance-based biosensors," Biosensors and Bioelectronics 26, 1815–1824 (2011).

[2] R. Kashyap and Galina Nemova," Surface Plasmon Resonance-Based Fiber and Planar Waveguide Sensors," Journal of Sensors (2009).