Terahertz transmission through femtosecond-machined metal structures

J. U. Lee, M. Seo, and D. S. Kim
School of Physics, Seoul National University, 151-747 Shillim Dong, Kwanak Gu, Seoul, Korea
denny@snu.ac.kr

S. C. Jeoung
Optical Nano Metrology Group, Korea Research Institute of Standards and Science, Daejeon 305-304, Korea

Q-Han Park
School of Physics, Korea University, 136-701 Anam-dong, Sungbuk-Gu, Seoul, Korea

Abstract Using THz time-domain spectroscopy, we study plasmonic band gaps in periodic metal arrays of slits. Femtoseocnd machinming system guarantees good quality sub millimeter structures for THz spectroscopy. Fabry-Perot effect enhances the transmission when the two resonances cross but does not alter the surface plasmon peak positions.

Surface plasmon polaritons have become a topic of intense current interest, ever since the so-called surface plasmon enhanced transmission has been discovered in periodic metallic structure with subwavelength holes [1]. One of the outstanding issues concerns the role of Fabry Perot effects especially in subwavelength slits [2]. In the microwave region, Fabry-Perot effect has been found in *single* slits. Terahertz time domain spectroscopy has begun to give important insights on the role of surface plasmon polaritons both in doped semiconductors and in metal rods [3]. In this paper we show that the effect of Fabry-Perot resonance on *multiple* slits is to enhance the transmission when the Fabry-Perot resonance crosses one of the surface plasmon diffraction orders. This is in contrast with single slit case in the microwave regime, where the Fabry-Perot effect *determines* the transmission peak positions.

The samples used in this study were metals such as stainless steel or aluminum. Femtosecond laser machining generates relatively clean cleavages on these metals. Amplified 150 fs long Ti sapphire laser which delivers pulses with energy of up to 1 mJ at 800 nm at a repetition rate of 1 kHz irradiate samples above their threshold fluence. The fundamental output of the laser was delivered to the galvanometer scanner (Scanlab AG, Germany) and fast optical shutter with a rising time less than 0.5 ms was used in order to control the laser exposure. A telecentric lens (Sill Optics, Germany) with a focal length of 85 mm was employed to focus the laser beam on the substrate. A Gaussian spatial beam profile with a radius of ~ 40 μm in the spot was achieved. Figure 1 shows samples thus machined.

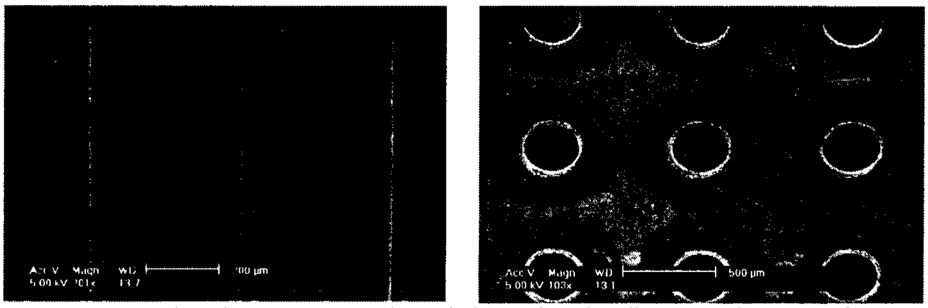

Figure 1. Femtosecond machining system can be applied to make sub millimeter sized structures for THz spectrosccpy.

We have used THz time-domain spectroscopy (Fig. 2(a)) to detect transmission profiles using a semi-insulating GaAs emitter biased with a 50KHz and 300V square wave to generate high power THz waves [4]. The samples are free-standing stainless steel plates with slits of various widths, sample thicknesses, and periods. Figure 2 shows time-domain traces and the resulting transmission spectra of sample A, which has slit period of 656 μm, sample thickness of 153 μm and slit width of 200 μm. Both the time domain traces and the transmission spectra show marked changes as the sample is tilted.

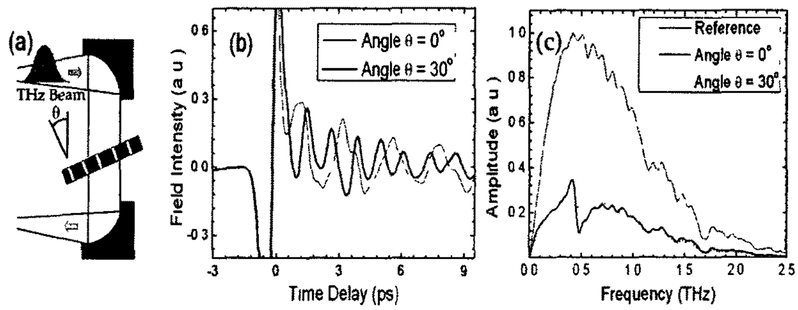

Figure 2 (a) Experimental setup (b) Time-domain traces of sample A with slit period of 656μm, thickness of 153 μm and slit width of 200 μm Time-domain signals for two incident angles show considerably different oscillations (c) Transmission spectra calculated by Fourier transform from these time-domain traces

Angle dependent transmission spectra are plotted in Fig 3 where white lines represent the location of surface plasmon modes at the air-metal interfaces In the THz frequency range, the real part of the metal dielectric constant is of the order of -100,000 and therefore surface plasmon modes correspond exactly to the Rayleigh wavelengths [5] THz time domain spectroscopy measures both the amplitude and phase of the transmitted light, and strong change of spectral phase, related to the Fano-like lineshapes [6], accompanies some of the surface plasmon resonances as shown in Fig 3(b)

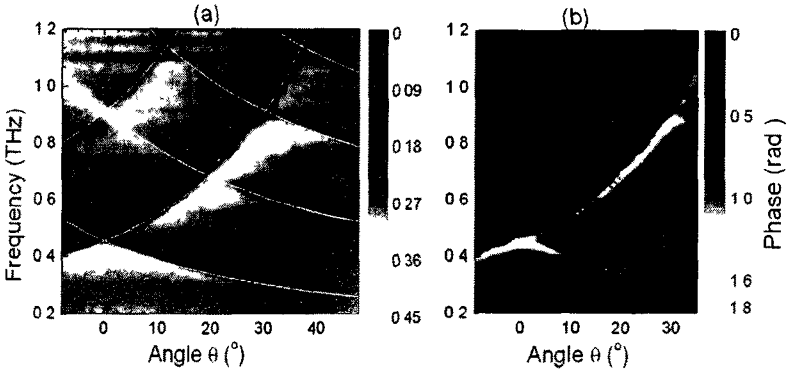

Figure 3 (a) Angle dependence of the transmission spectra for sample A White lines represent the surface plasmon resonances of various diffraction orders (b) Angle dependence of phase showing phase jump around the two dominant transmission peaks

In conclusion, we have performed terahertz time domain spectroscopy of plasmonic band gap structures fabricated by femtosecond machining It has been shown that the Fabry-Perot resonance does not result in new peaks but enhances the existing peaks when the two resonances cross each other

References

[1] T W Ebbesen, H J Lezec, F F Ghaemi, T Thio and P A Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," Nature 391, 667 (1998)

[2] J A Porto, F J Garcia-Vidal, and J B Pendry, "Transmission resonances on metallic gratings with very narrow slits," Phys Rev Lett , 83, 2845 (1999)

[3] J Go mez Rivas, C Schotsch, P Haring Bolivar, and H Kurz, "Enhanced transmission of THz radiation through subwavelength holes," Phys Rev B 68, 201306(R) (2003)

[4] G.Zhao, R N Schouten, N van der Valk, W Th Wenckebach, and P C M Planken, "Design and performance of a THz emission and detection setup based on a semi-insulating GaAs emitter," Rev of Sci Ins 73, 1715 (2002)

[5] Lord Rayleigh, "On the dynamical theory of gratings," Rroc R Soc London, Ser A 79, 399 (1907)

[6] M Sarrazin, J p Vigeron, and J M Vigoureux, "Role of Wood anomalies in optical properties of thin metallic films with a bidimensional array of subwavelength holes," Phys Rev B 67, 085415 (2003)