Electromagnetic wave funneling through λ/10,000,000 nanogaps for microwave regime

Kwanghee Lee, Jeeyoon Jeong, Jiyeah Rhie, Young-Mi Bahk, and Dai-Sik Kim
Department of Physics and Astronomy, Seoul National University, Seoul, 151-747, South Korea

***Abstract*—We observe microwave funneling through few nanometer-wide gap arrays. Nanogaps having rectangular ring shaped geometries are fabricated by atomic layer lithography technique. Microwave transmittance in 10~40 GHz range is measured by vector network analyzer (VNA) connected with pairs of rectangular waveguides supporting TE_{10} mode. The peak transmittance of 2 nm width gap is about 45% and it corresponds to the electric field enhancement factor of over 10,000. Terahertz transmittance is also measured by time domain spectroscopy to further verify the funneling phenomena in microwave regime.**

I. INTRODUCTION

ELECTROMAGNETIC wave funneling through subwavelength metallic holes has been intensively studied for past few decades [1, 2]. It was reported that electromagnetic field can funnel through a metallic gap structure in deep subwavelength regime, even in the range of the gap smaller than the wavelength by a factor of over ten thousand [3]. Recently, new fabrication technique called atomic layer lithography enables strong funneling of millimeter wave through few nanometer-width gap [4, 5].

In this work, we investigate squeezing of electromagnetic wave into nanogaps in microwave regime. We measure transmittance of rectangular ring shaped metallic gap array having few nanometer width for giant funneling and a perimeter of few millimeter for operation at Ka band (26.5~40 GHz). Sample is fabricated by atomic layer lithography with enhanced stability by introducing sacrificial layer deposition and chemical etching process [6]. Microwave transmittance of about 45% is observed with the nanogap array of 2 nm width. We also measure transmittance by terahertz time-domain spectroscopy (THz-TDS) [7] to verify and compare with microwave transmittance.

II. RESULTS

Microwave transmittance is measured by three pairs of open-ended rectangular waveguides (62EWGN, 42EWGK, and 28EWGK, Chengdu AINFO inc.) connected to a VNA (Vectorstar MS4644A, Anritsu). Figure 1(a) shows the schematic of experimental apparatus. WR62, WR42, and WR28 rectangular waveguide pairs supporting fundamental TE_{10} mode are used for 10~18, 18~26.5, and 26.5~40 GHz range, respectively. With careful thru-reflect-line calibration before measurement, we extend the frequency window of WR62 pair up to 10~18 GHz despite the waveguide attenuation below 12 GHz. When we measure microwave transmittance, the sample is aligned to the center of the waveguide pair and then clamped by two waveguide ports. Although this procedure can possibly damage the sample, our modified atomic layer lithography ensures enough structural stability.

Our fabricated nanogap array consists of a rectangular ring-shaped holes array filled with few-nm-thick Al_2O_3 surrounded by gold film. Detailed fabrication procedure is well described in reference [6]. Figure 1(b) shows the cross sectional image of 10 nm width and 100 nm height gold-Al_2O_3-gold gap (not used in the measurement). We cut the nanogap by focused ion beam after platinum deposition for preventing damage to the gap, and obtain a cross section by scanning electron microscope. Figure 1(c) is the dark field microscope image of the nanogap array used in our measurement, which has a geometry of 50 μm by 3,200 μm rectangular ring with 2 nm width and 100 nm height. Separations between adjacent rings in both vertical and horizontal directions are 50 μm. As shown in the image, densely packed nanogaps with extreme aspect ratio of perimeter and width is achieved with high yield over large area.

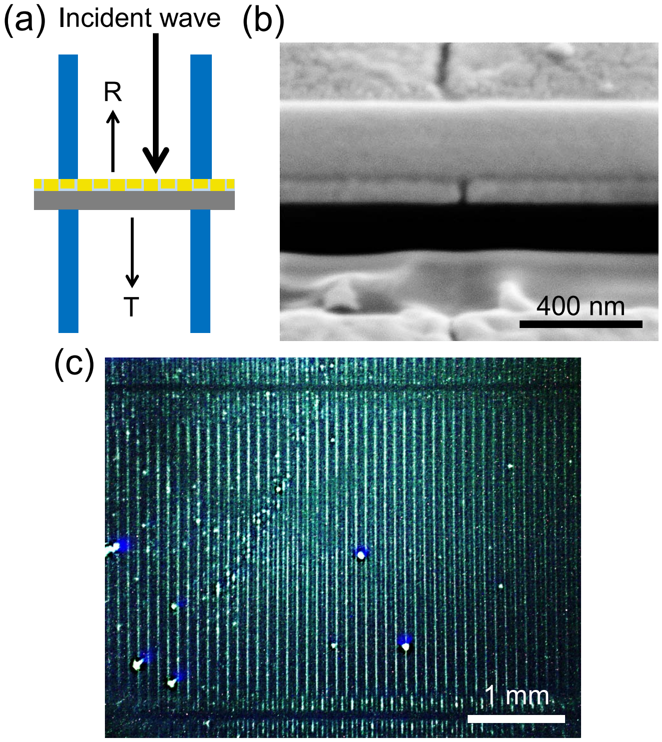

Fig. 1. (a) A schematic of experimental setup. Sample is sandwiched between open-ended waveguide pairs connected to VNA. (b) Cross section of 10 nm width gap (not used in this work) obtained by scanning electron microscope. (c) Dark field microscope image of 2 nm width gap array. Nanogaps are formed at the rim of 50 μm by 3200 μm rectangular array, separated by 50 μm in both vertical and horizontal directions.

Figure 2 exhibits the transmittance and electric field enhancement factor of nanogap array in the microwave and terahertz regime. Each microwave transmittance from different waveguides is normalized with respect to the substrate transmittance and plotted in a single graph. Owing to the misalignment of the sample, transmittance curve has discontinuities at the ends of waveguide frequency windows. However, these discontinuities are in the acceptable range of 2%

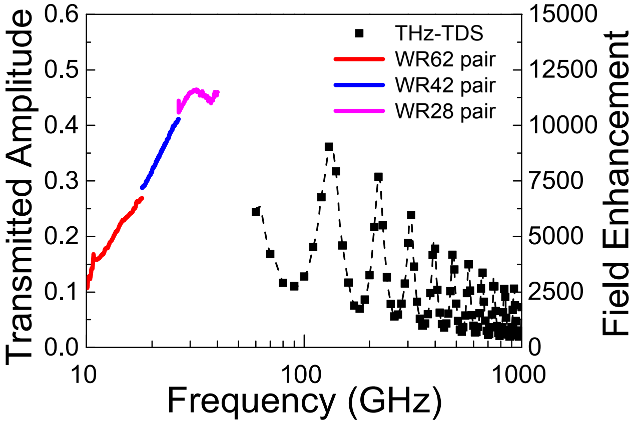

Fig. 2. Transmittance of 2 nm width gap array at GHz and THz regime. WR62, WR42, and WR28 waveguide pairs are used to measure transmittance in the 10~18, 18~26.5, and 26.5~40 GHz range, respectively. THz spectrum is obtained by THz-TDS. Scanning range of THz-TDS is set to 100 ps, so the frequency resolution is 10 GHz. Black dashed line is the fast Fourier transformed time trace with zero padding. Field enhancement factors are deduced from dividing transmittance by coverage ratio, the portion of transparent region (nanogap) in the illuminated area.

transmittance difference, so we can find the obvious trend of microwave transmittance. Peak value of normalized microwave transmittance is about 45% at 32 GHz. It is well known that a ring structure resonates when the wavelength of incident wave matches to the perimeter of the ring. Since the refractive index of silicon substrate is 3.4, the effective refractive index considering also the alumina gap is about 2.5 [8]. So the expected resonance frequency is about 37 GHz, which is comparable to the measured peak frequency if we consider that the resonance frequency may be affected by periodicity and imperfections of the sample structure. The transmittance value of 45% implies that the electric field is intensified in the nanogap by a factor of over 10,000, since nearly all the transmitted wave comes from the dielectric gap occupying only 0.004% of the whole sample area [9].

We measure terahertz transmittance of the same sample with THz-TDS to supplement the microwave transmittance. To obtain data of sub-THz frequency range, we set a sufficient scanning range in time domain of 100 ps. In this case, frequency resolution of fast Fourier transform is 10 GHz, the reciprocal of the scanning range. Multiple peaks of terahertz transmittance come from the Fabry-Pérot resonance related to the thickness of substrate. Although there is a blank of transmittance data between 40~60 GHz, it is clear that the two traces of transmittance match each other. Therefore, we hereby confirm that microwave can indeed funnel through nanogap which is ten million times smaller than its wavelength.

III. SUMMARY

We investigated the funneling of microwave through few nanometer width metallic gap structure. Sample was fabricated by atomic layer lithography with modifications for further yield and stability. Microwave transmittance was measured by three pairs of rectangular waveguides connected to VNA, after thru-reflect-line calibration. We observed 45% transmittance at 32 GHz, corresponding to the electric field enhancement factor of over 10,000. Terahertz transmittance was also measured and shows good agreement with the result of microwave regime. Our work paves path towards the combined research area of nanotechnology and microwave technology.

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