Anomalous terahertz transmission in bow-tie plasmonic antenna apertures

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Received March 30, 2011; revised June 8, 2011; accepted June 12, 2011; posted June 20, 2011 (Doc. ID 145115); published July 28, 2011

Arrays of subwavelength dipole bow-tie apertures are designed and characterized at terahertz frequencies. For an incident terahertz field perpendicular to the longer axis of the bow tie, a strong resonance enhancement, line narrowing, and a nonmonotonic frequency shift were observed with increasing length of the tapered bow-tie arms. Such characteristic behaviors primarily originate from localized surface plasmon resonances. In addition, with a decreasing aperture size, the contribution of localized plasmons becomes prominent due to an increase in plasmonic lifetime as the terahertz pulses strongly couple with the metallic surface surrounding the bow-tie apertures. © 2011 Optical Society of America

OCIS codes: 300.6495, 050.6624, 240.6680.

Resonant transmission of electromagnetic waves through plasmonic subwavelength geometries has attracted enormous attention due to its interesting physical mechanisms and fascinating applications in a variety of fields [1–3]. In general, the transmission enhancement is primarily attributed to resonant excitation of surface plasmon polaritons (SPPs) arising from the surface periodicity [4,5]. Recent studies, however, indicate that the localized surface plasmon (LSP) resonance associated with the hole shape also plays a role in the enhanced transmission [6]. Optical properties of different types of apertures have been studied at various frequencies over the last few years [7–12]. To improve transmission efficiency, a special type of aperture in a bow-tie shape has been investigated recently [13–16]. Experimental results have demonstrated that the intense interaction between two closely spaced triangular slots leads to a strong field enhancement [13] and localization [14,15] compared to those of square and rectangular apertures with the same filling fraction. Moreover, the enhanced transmission and light confinement is promising in high-resolution optical imaging [16], high-density optical storage, and nonlinear optical phenomena. The complex plasmonic structures and their coupling effect to the radiation field has been a topic of intensive theoretical and experimental studies [17].

Although investigations have been carried out on isolated [18] and tip-to-tip [13–16] triangular slots at visible and near-IR frequencies, plasmonic properties of bow-tie apertures with respect to the tip length yet remains unspecified, particularly when it is much greater than the width of the bow-tie unit cell. Also, with extensively increased conductivity of metals in the terahertz regime, the bow-tie geometries are expected to present unique plasmonic properties that were not observed at higher frequencies. In addition, the well-developed lithographic processing allows for precise control over the dimensions of the microstructured bow-tie unit cells functioning at terahertz frequencies, thus enabling systematic and highly reproducible studies of their resonant properties.

In this Letter, plasmonic properties of dipole bow-tie antenna apertures are investigated using terahertz time-domain spectroscopy (THz-TDS) [19,20]. It was found that the shape of the bow-tie unit cells greatly affects the transmission enhancement and induces strong polarization anisotropy. The tip-length-dependent transmission presents a characteristic evolution in resonance magnitude, linewidth, and resonance frequency. Based on numerical simulations, we find that transmission properties of the periodic bow-tie apertures in the terahertz regime are primarily associated with resonant excitation of LSPs.

The bow-tie antenna samples were fabricated by conventional photolithography and metallization processing. A 280-nm-thick Al film was deposited on a n-type, 0.64-mm-thick silicon wafer with a resistivity of $12\,\Omega\cdot$cm. Figure 1 shows the microscopic images of a set of fabricated bow-tie unit cells. Each sample, with dimensions of $10\,\text{mm}\times 10\,\text{mm}$, is composed of periodic bow ties of a fixed arm length, width, and tip-to-tip gap of 90, 20, and $2\,\mu$m, respectively, and various bow-tie tip lengths, Δl, ranging from 0 to $90\,\mu$m. The periodicities in the x and y directions are 80 and $204\,\mu$m, respectively. A blank silicon wafer identical to the array substrate is used to obtain the reference terahertz pulses. The arrays are characterized by a photoconductive switch-based broadband THz-TDS system, as described in [20]. The

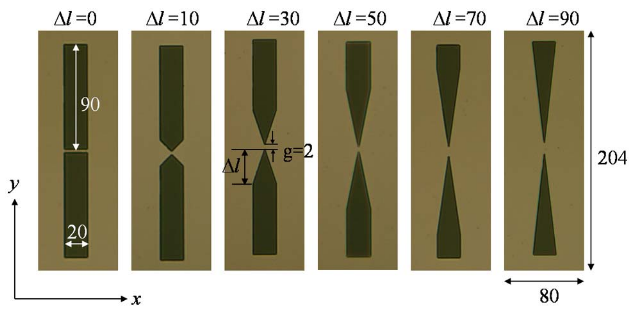

Fig. 1. (Color online) Microscopic images of lithographically fabricated bow-tie unit cells. All dimensions are in micrometers.

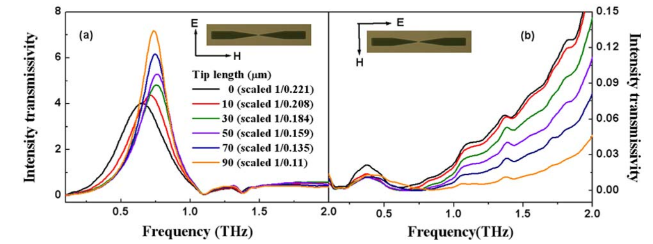

Fig. 2. (Color online) (a) x-polarized and (b) y-polarized frequency-dependent normalized transmittance of dipole bow-tie apertures of different tip lengths.

transmission measurements were performed with a linearly polarized terahertz wave at normal incidence.

The power transmission (transmittance) of the arrays was measured and normalized to the open fraction of the bow-tie unit cells [21]. As shown in Fig. 2, the normalized transmittance reveals that the shape and size of the apertures have tremendous effect on the resonant properties. For the x-polarized terahertz wave, two resonances were observed at 0.7 and 1.35 THz. According to the momentum matching condition [1], the calculated fundamental $[0,1]$ and $[1,1]$ SPP modes due to periodicity are located at 1.1 and 1.5 THz, which are much higher than the measured peaks. According to recent in-depth studies on LSPs, the observed redshift could be primarily a result of resonant excitations of LSPs and their coupling with SPPs [13,21–23]. On the other hand, all the minima are associated with so-called Wood's anomalies [24], which are unaffected by the tip length of the bow ties.

As the tip length varies, an effect that is immediately noticeable is the modification in transmittance at the resonance peaks. At the $[0,1]$ mode resonance and with an x-polarized terahertz wave, we observed an increased normalized transmittance from 4 to 7.2 when the tip length was changed from $\Delta l = 0$ to $90\,\mu$m. This indicates that the relative contribution of the resonant transmission is getting prominent as the bow-tie tips become sharper with decreased aperture porosity. With the y-polarized terahertz wave, however, an increase in the tip length leads to a reduced transmittance, as shown in Fig. 2(b). All the measurements reveal that the transmission for the x-polarized terahertz field is more than 2 orders of magnitude stronger than that of the y-polarized field. Similar polarization anisotropy behavior was also observed in the rectangular hole arrays [22].

In addition to the transmittance magnitude, resonance frequencies are also closely correlated to the shape of the apertures. Here, our discussions focus on the resonance shift observed with the x-polarized terahertz wave. With an increasing tip length up to $50\,\mu$m, the lower-frequency resonance blueshifts from 0.65 to 0.76 THz. With further increase in the tip length beyond $50\,\mu$m, however, the resonance shifts in an opposite direction, i.e., it redshifts. A bow-tie aperture with $\Delta l = 90\,\mu$m resonates at 0.74 THz.

Transmission properties of the bow-tie arrays are further explored by finite-element simulations using CST Microwave Studio. Figure 3(a) shows the calculated resonance frequencies of the periodic (open circles) and random (solid circles) bow-tie apertures with various tip lengths ranging from 0 to $90\,\mu$m. Similar to the experimental observation (squares), the resonance frequency

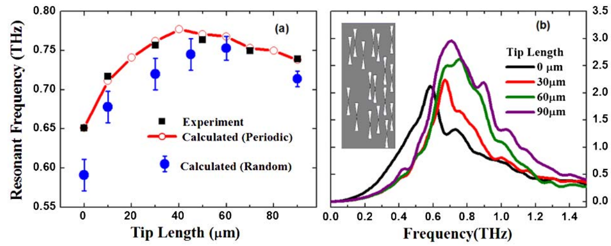

Fig. 3. (Color online) (a) Simulated resonance frequencies for periodic (open circles) and random (solid circles) bow-tie apertures versus the tip length. The experimental results are denoted by the solid squares for comparison. (b) Calculated normalized transmittance of the random arrays of different tip lengths.

of the periodic array blueshifts as the tip length increases from the minimum ($\Delta l = 0$) up to $\Delta l = 40\,\mu$m. It then redshifts with a longer tip until the aperture becomes a full bow tie. This finding is quite different from the monotonic change in resonance frequency observed in the rectangular hole arrays due to nonresonant contributions [23] or the bow-tie-slots due to periodicity of the array [25].

It is also interesting to note that the transmission through random arrays of such bow-tie apertures maintains a consistency in comparison with those of the periodic counterparts. Figure 3(b) shows the normalized transmission of four different random arrays where the longer axis of the bow ties remains along the y direction, while their relative positions are random, as shown in the inset of Fig. 3(b). Clearly, with a longer tip and decreased porosity, the resonant transmittance of the randomly arranged bow ties becomes stronger and the peak resonance reveals a similar trend in frequency shift with that of the periodic arrays, whereas the transmittance strength becomes lower than that of the periodic counterparts. Overall, the calculations confirm that SPPs do contribute to the transmission enhancement, whereas the resonance positions and linewidth are dominated by LSPs.

Finally, we explore the resonance linewidth behavior with respect to the shape of the bow ties. The measurement showed that the resonance linewidth becomes narrower with increasing length of the bow-tie tips. To achieve a clear understanding of this behavior, we characterized the lifetime of the plasmon wave by looking at the time-domain signals. The terahertz waveforms transmitted through the arrays with tip lengths of 0 and $90\,\mu$m are shown in Fig. 4(a). The transmitted pulses can be

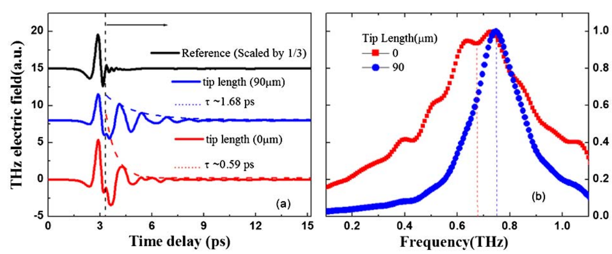

Fig. 4. (Color online) (a) Time-domain terahertz pulses through free space and the bow-tie arrays with tip lengths of 0 and $90\,\mu$m, and (b) Fourier-transformed normalized spectra of the time-domain waveforms after 3.3 ps.

divided into two sections: (i) the main transmission pulse (before 3.3 ps) and (ii) oscillations (after 3.3 ps); this corresponds to a radiation that couples to the excited plasmon resonance before being transmitted [26,27]. The lifetime of the plasmon wave decreases with increasing aperture size.

The Fourier-transformed spectra of the waveforms were calculated in the range of 3.3 to 15 ps, where the oscillation component was observed. The normalized power spectra for the tip lengths of 0 and 90 μm are shown in Fig. 4(b), where the transmission peaks are observed at 0.67 and 0.75 THz, respectively, which are consistent with the resonance frequencies shown in Fig. 2(a). Thus, this oscillation component is clearly originated from LSPs resonantly excited in the vicinity of the bow tie.

To further characterize the lifetime of the surface mode, we fit the oscillation component of the measured waveforms using a damped harmonic oscillator function [27]. For the exponential envelope shown in Fig. 4(a), the lifetime of the plasmon resonance increases from 0.59 ± 0.05 to 1.68 ± 0.05 ps with a decreasing filling fraction from 22% to 11%. Figure 4(b) also reveals the correlation between the resonance lifetime and linewidth. As the lifetime is inversely proportional to linewidth, arrays with smaller apertures tend to enable LSPs of longer lifetime and, consequently, a narrower linewidth in the frequency domain. This result agrees well with the previous work, which suggested that the lifetime of a surface wave (SW) increases with decreasing hole diameter as the spatial attenuation length of the SW in the direction normal to the metal surface increases and the intensity of the SW is localized [27].

This work was supported by the U.S. National Science Foundation (NSF) and the National Natural Science Foundation of China (NSFC) (Grant No. 61028011).

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