Resonance properties of THz plasmonic dipole-bowtie antenna array: The critical role of the substrate*

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Subwavelength arrays of dipole-bowtie antennas are designed and characterized using terahertz time-domain spectroscopy (THz-TDS) and finite element method (FEM) simulations. Two different substrates, silicon and mylar with an order of magnitude difference between their thickness values are used to study the resonance properties of the antennas. The 640-μm thick silicon substrate supports a sharper fundamental mode resonance. We discover that higher-order Fabry–Perot resonances can be excited only in 24-μm thin mylar substrates and show much higher sensitivity to dielectric changes in the environment and the geometrical parameters of the antennas than the fundamental dipole resonance.

Keywords: THz-TDS, dipole-bowtie antennas, plasmonic resonator

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1. Introduction

Optical antennas with different shapes and sizes provide a unique and effective means to concentrate and manipulate light on a nanoscale through the excitation of collective electron oscillations known as surface plasmons (SPs), and have enabled a wide variety of optical sensing and spectroscopy techniques.[1–3] The optical properties of optical antennas with dipole or bowtie shapes have been discussed over the last few years.[4–8] The strong field enhancement in dipole antenna has readily been shown by white light continuum generation.[4] Bowtie antennas have recently been used as near-field probes[5] and for nanolithography.[6] The potentials of both structures for the enhancement of the fluorescence of molecules have also been demonstrated.[7,8] However, their abilities to tune the plasmonic resonances depending on different geometrical parameters and the essence of their interaction with light yet remain to be fully explored. Also, at visible frequencies, the fabrications of such geometrical structures continue to be a challenge. The typical process for the fabrication of such plasmonic structures is a lithographic technique, i.e., electron beam lithography[9] and/or photolithography,[10] where a relatively thick glass or semiconductor wafer substrate is used. They are made from the noble metals to avoid the stronger dispersion, their dimensions as small as a few tens of nanometers are at the limit of today's fabrication techniques, and high-permittivity or a thick substrate contributes to the large loss in the resonator. Hence, designing smaller antennas by means of high index substrates does not seem to be a practical approach to capturing the nature of their operation.

In the terahertz regime, however, most metals become highly conductive.[11–14] Thus, the metallic antennas are expected to present unique plasmonic properties that were not observed at higher frequencies.[15] In addition, the advantage of exploring such subwavelength structures at terahertz frequencies is to use the well-developed photolithographic processing to realize the precise control over the dimensions of the micro-structured antennas, which enables systematic and highly reproducible studies of their resonant properties. In this paper, we design a series of dipole-bowtie antennas and fabricate them using two different substrate materials, i.e., 640-μm Si wafer and 24-μm Mylar film. Terahertz time-domain spectroscopy (THz-TDS) is used to characterize their plasmonic resonant evolution from dipole antenna to bowtie antenna. In addition, based on finite-element simulations, the frequency shifts of the fundamental and higher-order resonances are also investigated in terms of the tip length of the tapered bowtie arms and the dielectric changes of the substrates.

2. Experiments

The bowtie antennas were fabricated by conventional photolithography and made of optically 200-nm thick aluminum on 640-μm thick silicon substrates (p-type resistivity 12 Ω·cm). Figure 1(a) shows the microscopic images of a set of fabricated bowtie unit cells. Each sample, with a dimension of 10 mm×10 mm, is composed of periodic bowties of a fixed arm length (L), width (w), and tip-to-tip gap (g) values of 90, 20, and 2 μm, respectively, and various bowtie tip lengths, Δl ranging from 0 μm to 90 μm. The periodicities in the x and

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y directions are 80 μm and 204 μm, respectively. For comparison, we also fabricate bowtie antennas with identical geometries on 24-μm-thin Mylar film. The samples were experimentally characterized by THz-TDS in a broadband, photoconductive switch-based system that consists of four parabolic mirrors in an 8-F confocal geometry.[16,17] The dipole bowtie antennas are penetrated by the focused THz beam at normal incidence and with the polarization being parallel to the longer axis of the bowtie.

The geometrical parameters and substrate materials strongly influence the plasmonic resonance in dipole bowtie antennas, as indicated in Figs. 2(a) and 2(b). For gap antennas deposited on the Si substrates, the first-order dipole resonances are centered at around 0.7 THz and present a slight frequency shift and line narrowing with increasing the lengths of the tapered bowtie arms, while the antennas on the Mylar films feature a main peak centered at 1.2 THz. In addition, their spectra appear more complex with high-order resonance at higher frequency.

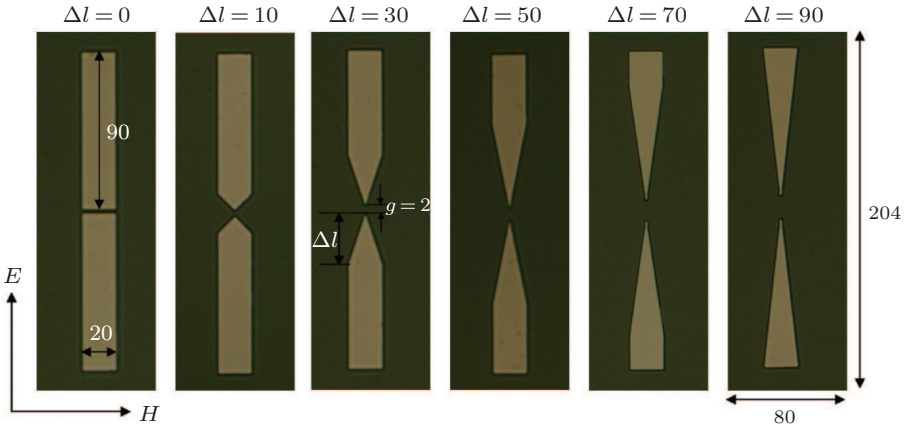


Fig. 1. (color online) Microscopic images of lithographically fabricated bowtie unit cells. All dimensions are in μm.

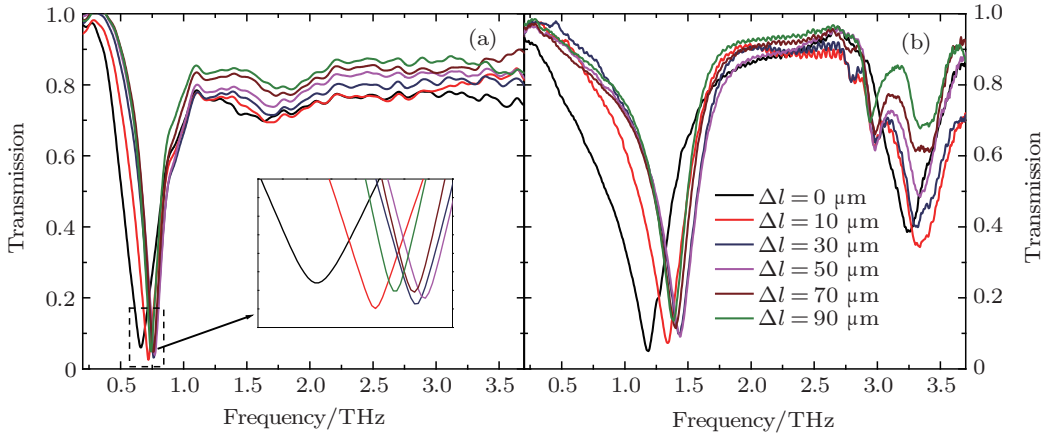


Fig. 2. (color online) Frequency-dependent transmissions of dipole-bowtie antennas fabricated on bulk Si substrate (a) and thin Mylar film (b).

3. Discussion

As shown in Figs. 2(a) and 2(b), the first-order dipole resonance (fundamental mode) appears to have a nonmonotonic shift in frequency and a monotonic change in linewidth, in the two cases, i.e., (i) the resonance frequency blue-shifts with tip length increasing up to 50 μm and (ii) the resonance reverses its trend and begins to red-shift with the tip length further increasing above 50 μm. Furthermore, the resonance linewidth becomes more and more narrow when the tip length is changed from $\Delta l = 0$ μm to 90 μm, indicating the enhancement of electric field at the tip and an increase in the quality (Q) factor of the resonator.

To gain an insight into the relation between the resonant frequency and the tip length (Δl), we carry out finite-element simulations using the CST Microwave Studio. In the case of the first-order dipole mode and Si substrates, the calculated resonance frequencies of the dipole-bowtie antennas with different tip lengths ranging from 0 μm to 90 μm are shown in Fig. 3. Like the experimental observation, the resonance blue-shifts from 0.62 THz to 0.71 THz with the tip length increasing up to 40 μm (See Fig. 3(a)). As the tip length further increases

above 50 μm, however, the resonance shift reverses and red shifts (See Fig. 3(b)). A bowtie antenna with $\Delta l = 90$ μm appears to resonate at 0.64 THz.

The distributions of the electric field for all antennas at the resonant frequencies are dominated by a substantial signal confinement and enhancement in the gap area, as indicated in Fig. 4. In addition, the field inside the gap of each of these bowtie antennas seems to provide a better localization than that observed in a dipole structure. For all investigated antenna geometries, the resonant frequency of gap antenna is slightly red-shifted with respect to the resonance frequency of the single antenna segment with a length of 90 μm (not shown) and rather blue-shifted in comparison with the resonance of the single antenna segment with an overall length of 180 μm (not shown). These simulation results confirm that the resonant properties of gap antenna are governed by the resonance of each individual arm and the near-field coupling results in the red shift of the resonant peak.[18,19] In addition, the resonance frequency is strongly influenced by the geometry of the antenna. The blue shift can be attributed to the decrease in the effective area of the dipole antenna,[20] while the red shift with bow angle decrease is due to enhanced near-field coupling between the pointed bowtie pairs.[21]

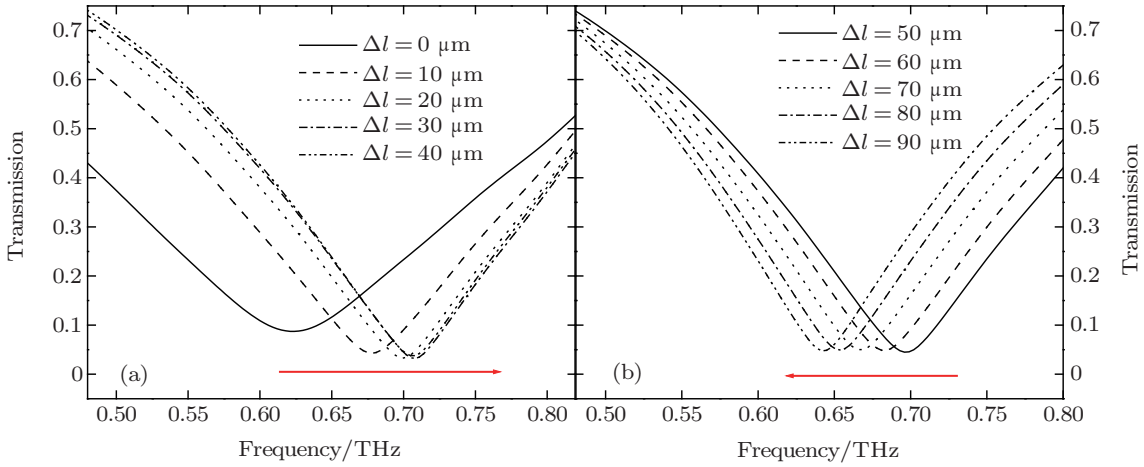


Fig. 3. Simulated frequency-dependent transmissions of dipole-bowtie antennas with tip lengths ranging from 0 μm to 40 μm (a) and from 50 μm to 90 μm (b). All substrates are bulk Si wafers.

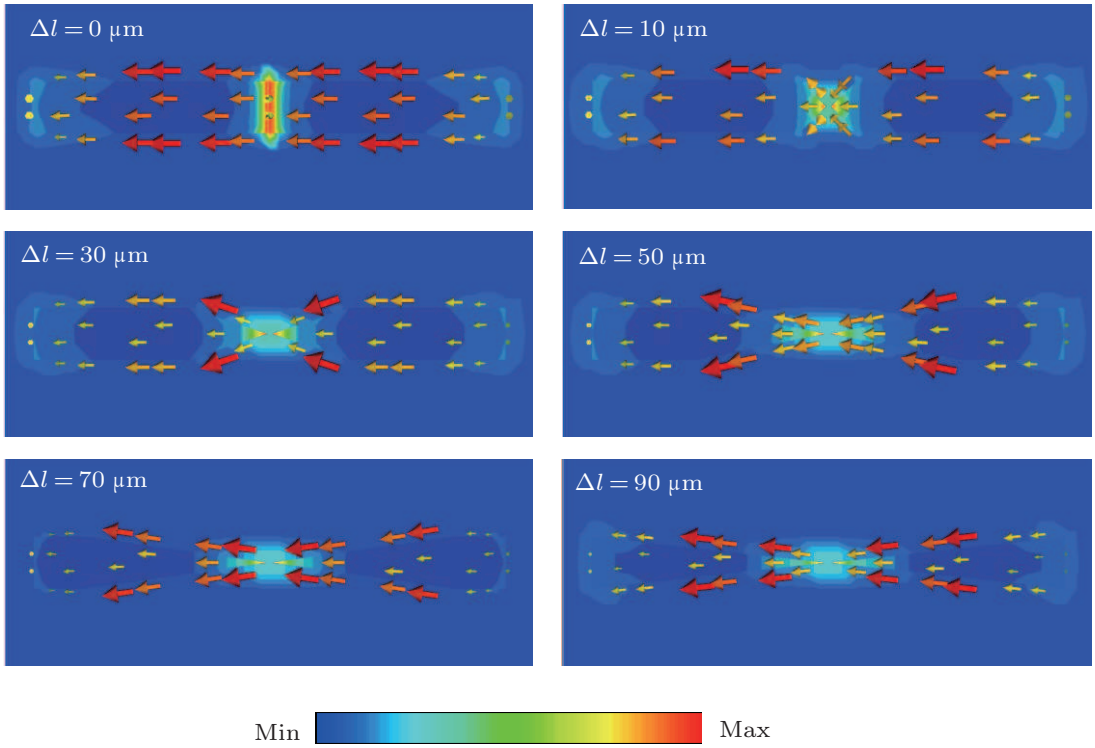


Fig. 4. (color online) Simulated surface currents and electric energy distributions at the resonant frequency.

In the case of Mylar substrate, the lower index (about 1.75) leads to a blue shift and linewidth broadening of the dipole resonance. We first observe the blue shift and then the red shift as the tip length increases in the bowtie antenna, just like Si substrate behavior. Surprisingly, in the spectral range from 2.7 THz to 3.7 THz, however, some high-order resonances become observable and they show a clear trend with the tip length increasing. At the smallest tip length, the dipole antenna has a resonance at 3.25 THz, where the transmission is about 0.38. In the transition from dipole to bowtie shape, this resonance splits into two dips and the spectral distance between them increases with the increase of tip length. In the case of the complete bowtie shape, there appear two resonances at 2.8 THz and 3.4 THz and the transmission is about 0.68. Based on the Fabry–Perot model and full-field electromagnetic simulations performed by Barnard *et al.*,[22] the high-order plasmonic resonances can be achieved through the excitation and constructive interference of SP waves that propagate back and forth between the terminations. The resonant angular frequency ($\omega_{\mathrm{res},m}$) for the single strip antenna can be expressed as

$$\frac{\omega_{\mathrm{res},m}}{c}2nL+2\phi = m\cdot 2\pi, \tag{1}$$

where m is the order of the resonance, ϕ is the phase pickup of the short range SP wave reflected from a terminated thin metal film, n is the refraction index of the substrate and L is the length of the strip. In our case, $n = 1.75$ and $L = 90$ μm. From Eq. (1), the difference between $\omega_{\mathrm{res},1}/2\pi$ and $\omega_{\mathrm{res},3}/2\pi$ is 1.90 THz, just matching the measured result of the dipole antenna. However, because of the changes in the terminal geometries for other antennas, the direction of the reflected SP waves changes and the resonant frequencies of these antennas are strongly dependent on the shape of the antenna. However, their plasmonic resonant evolution from dipole antenna to bowtie antenna remains to be explained.

The relation between the high-order dipole resonance and the modal field distribution is further explored by finite-element simulations. Here, the dielectric constants of the Mylar film ($\varepsilon = 3.1 + \mathrm{i}0.28$ from 0.2 THz–3.5 THz) are experimentally determined and extracted by applying the multiple-reflection approach described in previous publications.[23,24] The simulation results show that the position and strength of the high-order resonance are very sensitive to the tip length, as shown in Fig. 5(a). Like the experimental observation, the plasmonic resonance is essentially single mode with a tip length less than 50 μm. With the tip length further increasing above 50 μm, however, the antenna exhibits two resonances, whose spectral positions and transmissions depend on the bow angle. Figure 5(b) shows the electric field distributions for the resonant modes of the dipole and bowtie antenna, respectively. For dipole antenna, a strong field in the single mode does not build up at any of the extremities of the bars (as shown in Fig. 4), but rather concentrates at the inside of the arms. In the case of bowtie antenna, however, strong fields are still confined at the tips of the triangles for both plasmonic modes.

In addition, the position and strength of the high-order resonance are also very sensitive to changes of the substrate index of refraction and thickness (Figs. 6 and 7). In the cases of the high-order resonance and the dipole antenna, the resonance wavelengths of the single mode increase and their resonant strengths decrease with index and thickness increasing, as shown in Figs. 6(a) and 6(b).

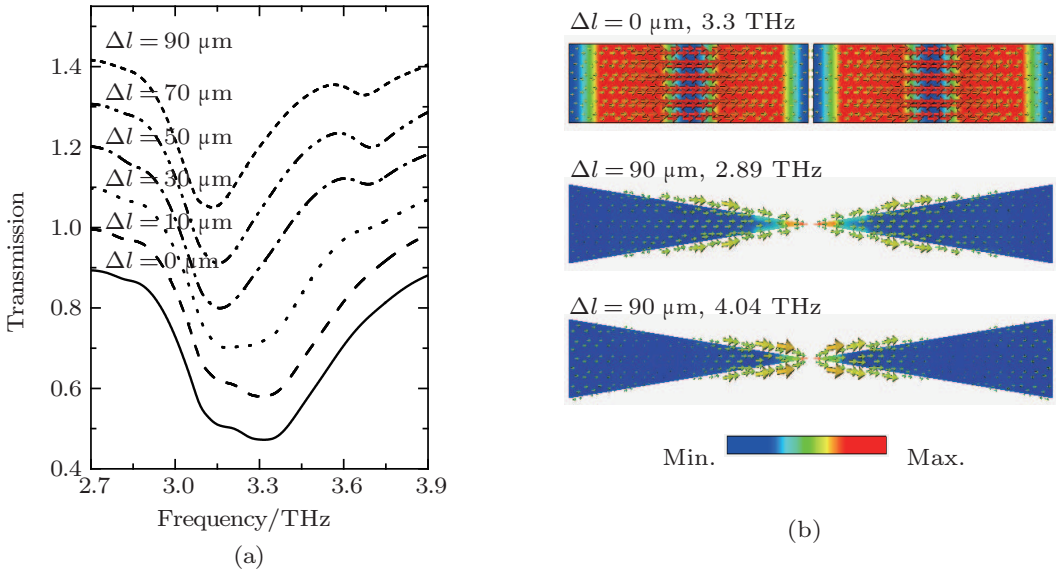


Fig. 5. (color online) (a) Simulated frequency-dependent transmissions from 2.7 THz to 3.9 THz of dipole-bowtie antennas with tip lengths ranging from 0 μm to 90 μm. All substrates are thin Mylar films. (b) Simulated surface currents and electric energy distributions at the resonant frequencies for dipole antenna and bowtie antenna, respectively.

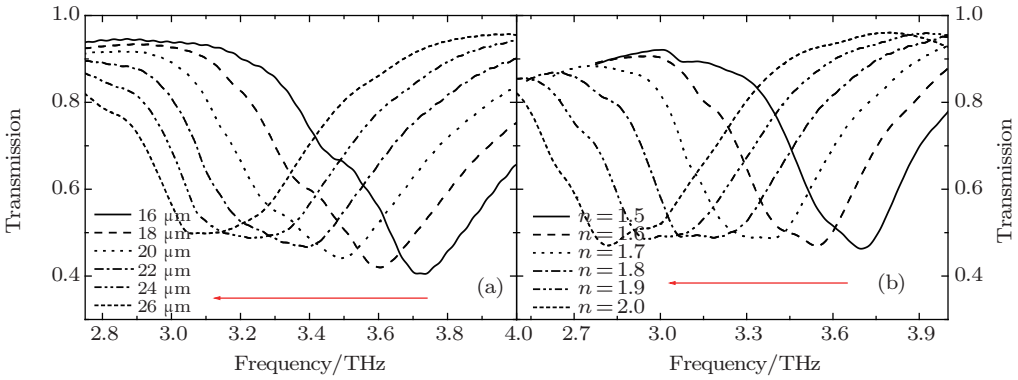


Fig. 6. Simulated high-order resonances of dipole antennas with different thickness values (a) and indices of Mylar substrates.

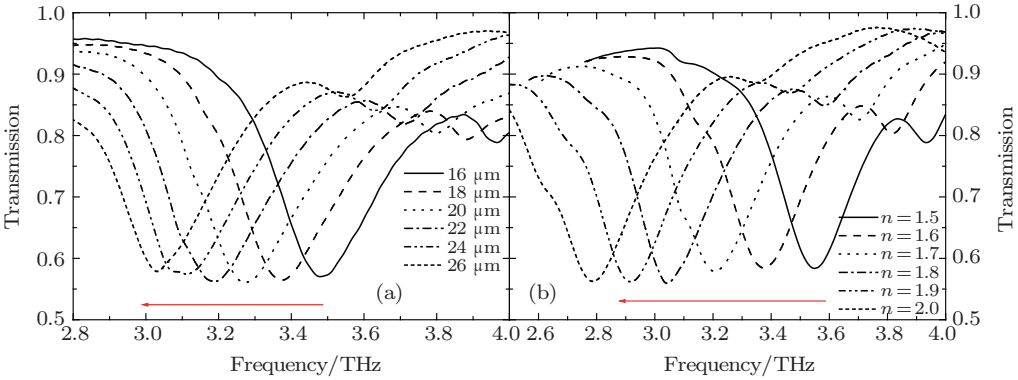


Fig. 7. Simulated high-order resonances of bowtie antennas with different thickness values (a) and indices of Mylar substrates.

For the high-order resonance and the bowtie antenna, however, not only the resonance wavelength of the double modes increase with index and thickness increasing, but also the second high-order resonance mode gradually disappears due to the high insertion losses of the high-permittivity and thick substrates, as shown in Figs. 7(a) and 7(b), just like the scenario of the Si substrate. So, a continuous adjustability in the resonance frequency can effectively be realized by tuning the substrate or coating material.

4. Conclusion

In this paper, we designed, fabricated, and characterized dipole-bowtie antenna arrays on bulk Si substrates and ultra-thin Mylar substrates at THz frequencies. We discovered that the resonant antenna array can support only the fundamental dipole mode resonance when fabricated on Si substrates, whereas the thin Mylar film substrates exhibit higher-order Fabry–Perot resonances, which undergo mode splitting as the shape of the antenna array changes from a dipole shape to a sharp-pointed bowtie shape. The Fabry–Perot resonances show significantly enhanced sensitivity as well as structural tuning, and thus indicate excellent potential for sensing applications.

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