Frequency Selective, High Transmission Spiral Terahertz Plasmonic Antennas

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ABSTRACT

Terahertz is long been studied and has potential in various applications. However, lack of efficient and sensitive detector is still an obstacle in the development of terahertz technology. The utilization of antennas can largely enhance sensitivity of terahertz detector. A bull’s eye plasmonic antenna has a great potential to sub-wavelength terahertz technologies because of its unique property of local electric-field concentration. However, a conventional bull’s eye antenna has a problem of a narrow band, limiting its ability for multi-frequency detection. Here we propose two terahertz plasmonic antennas for enabling arbitrary frequency selection: the split-joint bull’s eye structure and the spiral bull’s eye structure. We show that both of the two antennas can achieve wide-band transmission without large sacrifice on overall transmission. The frequency band can be arbitrarily tuned either by varying excitation directions or by adjusting structure parameters. These advantageous features will open up a door to frequency-selective terahertz antennas and their applications to multi-frequency investigations.

Keywords: Terahertz detection, Plasmonic, antenna Spiral bull’s eye antenna, High transmission, Frequency Selective.

INTRODUCTION

The spectral region of terahertz (THz) waves has been proven to have strong potential in various applications including security, medicine, food quality inspection, electronics, and astro-observation [1-4]. However, basic components for THz technology, such as detectors and sources, have not been fully established yet. This is mainly because THz frequency is too high in terms of high frequency electronics and its photon energy is much lower than that of visible light [5]. In order to further promote THz technologies, high-performance antennas are in strong demand along with detectors and sources.

Recently, a number of antenna designs have been studied for subwavelength optics which achieved high spatial resolution and high power throughput simultaneously [6-15]. Among them, a bull’s eye (BE)-shaped plasmonic antenna is one of the most promising candidates, since it can obtain high concentration and extremely large enhanced transmission beyond the diffraction limit [8]. Although there are no surface plasmon polaritons (SPPs) at THz region, spoof plasmons, which are electromagnetic waves that mimicking SPPs, can occur in THz region [16], enabling BE shaped plasmonic antenna to be used in THz analysis.

A conventional BE structure consists of a single subwavelength aperture surrounded by concentric periodic grooves. Though this structure is opening up a possibility of sub-wavelength THz analysis, one issue of this structure is narrow-band characteristics, which limits its ability for applications that need multi-frequency investigations, such as medical examination, molecular research, and astro-observation.

This paper proposes two methods to expand a frequency band of BE structure antennas and to arbitrarily select it, while maintaining their advantage of high transmission. First, we report the split-joint bull’s eye (SJBE) structures, and then propose the spiral bull’s eye (SBE) structure that is deduced from the SJBE structure. We analyze and compare performance of these BE structures through numerical simulation.
METHODOLOGY

Calculations in this paper were carried out using a 3D finite difference time domain method (Poynting of Optics, Fujitsu, Co., Japan). The simulation model is set as following. The Mur’s first-order absorbing boundary condition is applied to the calculation domain boundaries. As a THz source, a pulse at the frequency from 0THz to 10THz is used. The THz pulse is incident from the +z side at a normal incident angle on a gold film surface with a BE structure, and is set 600μm above the film surface. The thickness of the film t is 2μm, with an aperture of 100μm in diameter D.

Due to the narrow-band nature of a conventional BE antenna, its parameters depend on the desired frequency, as shown in Fig. 1. In this paper, parameters of designed BE structures are chosen as following to efficiently excite surface plasmons. The period of grooves \( \Lambda \) for BE structures is equal to the wavelength \( \lambda \) of the designed THz source. The width of groove is set to be half the period [17]. The depth of grooves \( h \) is equal to \( \lambda/10 \) [18]. The distance between the middle of the BE and the first groove \( C \) is set to be \( 5\lambda/2 \) [18].

RESULTS AND DISCUSSION

SJBE structure

We first describe the SJBE structure using two different methods of combining two independent BE antennas. The first one is a “half-half” method, as depicted in Fig. 2 (a). BE structures designed for 1THz and 1.5THz are split in half. Then the right part of the 1-THz BE and the left part of the 1.5-THz BE are jointed together to form a “half-half” SJBE structure. The second one is a “2-by-2 pieces” method, as shown in Fig. 2 (b), where the 1-THz BE and the 1.5-THz BE are split into quarters and then are jointed together to form a rotationally symmetric BE structure.

Due to the rotational symmetry of the “2-by-2 pieces” SJBE structure, the simulation results with pulse excitations along either x direction or y direction are the same. However, this is not the case for the “half-half” SJBE structure. Figure 2 (c) compares the transmission spectra for the 1-THz single BE model, the 1.5-THz single BE model, the “half-half” SJBE model, and the “2-by-2 pieces” SJBE model. The SJBE antenna can concentrate both 1-THz and 1.5-THz pulses. For the “half-half” model, the transmission is relatively higher when the incident pulse excites surface plasmon along y-axis. For the x-axis pulse excitation, the existence of interface between the two half bull’s eyes will affect the propagation of surface plasmonic waves, resulting in slightly lower transmission. While for the “2-by-2 pieces” model, the composed shape of the two 1-THz BE quarters is similar to a bow-tie antenna, which is commonly used in THz detection. The combination of the bow-tie shape and the bull’s eye grooves might lead to a higher transmission enhancement and higher electric field concentration. The same is true of the two 1.5-THz BE quarters. Since the transmission of the “2-by-2 pieces” SJBE structure is the highest compared to the other two situations, “n-by-2 pieces” model is used for further simulations.
Fig. 3. The structure of (a) the “6-by-2 pieces” SJBE antenna and (b) the “18-by-2 pieces” SJBE antenna. The transmission spectra of the “6-by-2 pieces” SJBE antenna and the “18-by-2 pieces” SJBE antenna when the incident pulse excites surface plasmon along (c) x-axis, (d) y-axis, and (e) both x-axis and y-axis.

Since the transmission spectra of a “2-by-2 pieces” SJBE is discrete, “6-by-2 pieces” SJBE structure and “18-by-2 pieces” SJBE structure are further proposed to make the transmission spectra more continuous. Figures 3 (a) and (b) display the structures of the “6-by-2 pieces” model and the “18-by-2 pieces” model respectively. To form the “6-by-2 pieces” antenna, BE structures for 1THz, 1.1THz, 1.2THz, 1.3THz, 1.4THz and 1.5THz are split by every 30 degree and are jointed together to form a SJBE. Similarly, in “18-by-2 pieces” antenna, BE structures from 1THz to 1.567THz are split by every 10 degree and are jointed together.

Figures 3 (c), (d), and (e) present the transmission spectra of these two structures. For the x-axis excitation, transmission spectra show two higher peaks at 1THz and 1.5THz respectively for both the “6-by-2 pieces” model and the “18-by-2 pieces” model. In contrast, for the y-axis excitation, transmission spectra become more continuous, and the peak appears at around 1.2THz and 1.3THz. This is due to the fact that the excitation of surface plasmon polarizations strongly depends on the lattice constant of grooves, \(a\), as expressed by Eq. (1) and Eq. (2)[19]:

\[
\beta = k \sin \theta \pm v_g \tag{1}
\]

\[
g = \frac{2\pi}{a} \tag{2}
\]

Here, \(g\) is the reciprocal vector of the grating, \(v = (1, 2, 3, \ldots)\), \(\beta\) is the propagation constant, \(\theta\) is the angle under which photons impinging at the surface normal, and \(k\) is the wave vector.

When the incident pulse excites surface plasmon along x-axis, the actual lattice constant \(a\), for 1-THz and 1.5-THz BE slices is close to their grooves’ period \(A\), so that the value of propagation constant \(\beta\) approaches the wave vector between the in-plane momentum. In this situation, surface plasmon polarizations in this region can be properly excited, leading to high transmission around these frequencies. In contrast, the actual lattice constant \(a\), for 1.2-THz and 1.3-THz BE slices is much larger than their grooves’ period \(A\), where the excitation direction of incident pulse is almost parallel to the grooves. In this case, surface plasmon polarizations cannot effectively be excited in this region, and consequently transmission around these frequencies becomes low.

Similarly, when the excitation direction is along y-axis, surface plasmon polarizations can effectively be excited around 1.2THz and 1.3THz, and the transmission is higher in these regions. For excitation direction along both x-axis and y-axis, where the surface plasmon polarizations can be well excited in most regions, transmission spectra is equally distributed from 1.1THz to 1.5THz. This exhibits the highest transmission among all the simulations for both the “6-by-2 pieces” model and the “18-by-2 pieces” model. This relation between transmission amplitude and excitation direction of surface plasmon gives the possibility of selecting a preferred frequency range by changing incident pulse excitation direction.

Transmission spectra for the “6-by-2 pieces” structure exhibits higher amplitudes but discrete spectra, compared to the “18-by-2 pieces” structure. This is because each slice of the SJBE is a narrow band, which allows only plasmons with single frequency to propagate through the surface. In the case of the “6-by-2 pieces” structure, each slice is larger than those of the “18-by-2 pieces” structure. Thus surface plasmon polarizations can be well excited for a wider angle, and the transmission amplitude increases as the incident angle of surface plasmon increases.
amplitude for a single frequency is larger. On the other hand, the “18-by-2 pieces” structure is composed of more but thinner slices, hence allowing surface plasmon polarization with more frequencies to be excited. As a result, the transmission spectra become more continuous.

**SBE structure**

According to the above calculations, we expect that the transmission spectra will be more continuous if segments for narrower frequencies are split and jointed together to form a complete BE structure. In an extreme case, when each slice’s angle is infinitely small, the grooves can connect smoothly within the semicircle. This forms a SBE structure.

For \( f_1 < f < f_2 \), edges of grooves are defined as Eq. (3):

\[
r = \frac{a}{4} \frac{c}{(f_2 - f_1) \pi} f_1, \ 0 < \varphi < \pi,
\]

\[
a = 5, 7, 9, 11, 13 \ldots \quad (3)
\]

When \( f_1 = 1 \text{THz} \) and \( f_2 = 1.5 \text{THz} \), groove edges are represented as Eq. (4):

\[
r = \frac{a}{4} \frac{150 \pi \times 10^{-6}}{2 \pi + \varphi} f_1, \ 0 < \varphi < \pi,
\]

\[
a = 5, 7, 9, 11, 13 \ldots \quad (4)
\]

There are two possible ways to joint the semicircle-SBE into one complete BE structure: a central symmetric one and a axial symmetric one. Figures 4 (a) and (b) depict the simulation model for these two types of SBE antennas respectively; sections in the grey square denote the calculation areas for these two models. For simulations of SBE structures, the grooves’ depth \( h \) equals to \( \lambda_1/10 \), where \( \lambda_1 \) is the wavelength corresponding to \( f_1 \).

Figures 4 (c), (d), and (e) display transmission spectra of the SBE structures. Clearly, the transmission spectra of the SBE structures are more continuous compared to those of the SJBE structures. The shape of transmission spectra also strongly depends on excitation direction of surface plasmon, enabling the selection of desired frequency domain via switching incident pulse excitation directions. At the same time, the transmissions are higher than that of the “18-by-2 pieces” SJBE structure. Therefore, the SBE structures have a relatively better performance compared to the SJBE structures.

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**Fig. 4.** The structure of (a) the axial symmetric SBE antenna and (b) the central symmetric SBE antenna. The transmission spectra of the SBE antenna when the incident pulse excites surface plasmon along (c) x-axis, (d) y-axis, and (e) both x-axis and y-axis.

**Fig. 5.** The electric field distribution on top of the central symmetric SBE antenna when the incident pulse excites surface plasmon along both x-axis and y-axis.

Fig. 6. The overall transmission of the SJBE antennas and the SBE antennas. “1” represents the 1-THz single BE structure. “6x”, “6y”, and“6xy” represent the “6-by-2 pieces” SJBE structure with x-directional, y-directional, and x-and-y-directional excitations. Similarly, “18x”, “18y”, and“18xy” denote the “18-by-2 pieces” SJBE structure for the three excitation directions; “Cx”, “Cy”, and“Cxy” denote the central symmetric SBE structure for the three excitation directions; “Ax”, “Ay”, and“Axy” denote the axial symmetric SBE structure for the three excitation directions.

Among the above situations, the central symmetric SBE structure for x-and-y-directional excitation shows the most continuously and equally distributed transmission spectra. Its transmission bandwidth is 5 times broader than that of a conventional single BE antenna. Figure 5 maps the electric field distribution on the surface of the central symmetric SBE for x-and-y-directional excitation. It indicates that the electric field density is highest in middle of the antenna, which demonstrates a high concentration of electric field.

Figure 6 presents the overall transmission of the SJBE antennas and the SBE antennas, compared to a conventional BE antenna for 1THz. The overall transmission was calculated by integrating all areas below the transmission spectra. The overall transmission of the “6-by-2 pieces” SJBE antenna for x-and-y-directional excitation is the highest, which corresponds to 77.6% of that of the 1-THz BE antenna. The overall transmission of the central symmetric SBE antenna for x-and-y-directional excitation equals to 62.0% of that of the 1THz BE antenna. These indicate that the SJBE and SBE antennas can realize wider-band transmission without large sacrifice on overall transmission, where minimum and maximum frequencies can be arbitrarily selected according to Eq. (3).

CONCLUSION
In conclusion, this paper proposes two designs of BE antennas, which enable wide-band THz transmission and arbitrary frequency selection. The SJBE structure consists of slices from single-frequency BE antennas. The SBE structure, which is derived from the SJBE structure, contains infinitely small slices of single frequency BE structures, making the connections between grooves continuous. In contrast to a conventional narrow-band BE antenna, the two proposed BE antennas have the ability to provide a wider transmission band without large sacrifice on overall transmission. These designs can be readily applied to wider or different frequency domain by simply changing structure parameters. This advantage is expected to make the BE structure a useful tool for multiple frequency investigations in sub-wavelength regions, which can be powerfully utilized in fields including nanomaterial and nanodevice characterization and molecular research.

ACKNOWLEDGEMENT AND FUNDING INFORMATION
This work was supported in part by the Japan Science and Technology Agency, the Funding Program for Next Generation World-Leading Researchers, MEXT/JSPS KAKENHI Grant Numbers 26286005, 26600010, 26103513, 26107516, and Support for Tokyotech Advanced Researchers (STAR).

REFERENCES


