Single sub-wavelength aperture with greatly enhanced transmission

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Abstract. High transmission efficiency at terahertz (THz) frequency is reported for a single aperture with sub-wavelength dimensions having a Siemens-star shape, microfabricated in the metal film and surrounded by periodic surface corrugations. Compared to theoretical predictions for a simple circular hole of equivalent area, up to $\sim 10^6$ transmission enhancements were observed experimentally. Such a pointed-shape aperture was also used to obtain the detailed profile of the electric field distribution in the focal plane of a linearly polarized focused THz beam. Applications could be extended to other regions of the electromagnetic spectrum by appropriate scaling of aperture microstructure.

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1. Introduction

According to diffraction theory of electromagnetic radiation by a single circular sub-wavelength aperture in a perfectly conducting plane screen,

\[ T_{\text{Bethe}} \approx \frac{64}{27\pi^2} \frac{S_a}{S_{\text{beam}}} (k \cdot r_a)^4, \]

where \( k = 2\pi/\lambda \) and \( T_{\text{Bethe}}, S_{\text{beam}}, S_a, r_a \) and \( \lambda \) are Bethe’s theoretical far-field plane-wave transmission, incident beam and aperture occupied areas, aperture radius and incident light wavelength, respectively. This expression is valid for normal incidence, \( k \cdot r_a \ll 1 \), \( 2\pi \) solid collection angle and \( S_{\text{beam}} > \pi(\lambda/2)^2 \) ([1] and references therein). For example, if \( S_{\text{beam}} = \pi\lambda^2 \) and \( r_a = \lambda/30 \), then \( T_{\text{Bethe}} \approx 5 \times 10^{-7} \). Consequently, very high power light sources and extremely sensitive detectors are needed to register such low transmission for any practical applications.

However, over the last decade, enhanced optical transmissions have been actually reported for modified sub-wavelength holes. Typically, such modifications involved the introduction of the scattering centres inside a single aperture ([2–4]; [5] and references therein; [6–8]) or dealt with the surroundings of the aperture by periodic corrugation in the screen ([9–13]; [14] and references therein; [15–17]). For example, a strong scattering intensity, \( I_s \), of incident field, \( I_0 \), at particular \( \lambda \) is expected from Mie theory [18] by placing metal particles with negative dielectric constant \( \varepsilon_m \) and radius \( r_p \) inside the aperture with positive dielectric constant, \( \varepsilon_a \), i.e. \( I_s \propto I_0 |r_p^3/\lambda^2(\varepsilon_m - \varepsilon_a)/(\varepsilon_m + 2\varepsilon_a)|^2 \). This approach was realized with some success in optimized fibre probes for scanning near-field optical microscopy (SNOM) [2, 3] and in very-small-aperture lasers (VSAL) [5]. Somewhat better \( T \) were reported for various ridge-type apertures [4, 5]. Among them, the best \( T \) were predicted and measured for bow-tie geometries [6–8]. From computational works, the scattering light spot was highly localized in the gap between the bow-tie tips with maximum normalized electric field, \( E \), intensities, \( |E|^2/|E_0|^2 \), reached up to \( 10^4 \) for optimal reported geometry and illumination conditions [7, 8]. Theoretically, the \( |E|^2/|E_0|^2 \) enhancements could be even larger for smaller tip gaps, higher tip sharpness and larger antenna arm to tip gap length ratios. However, the area of such enhancements inside the aperture also becomes smaller and experimental realization is limited by the resolution of microfabrication techniques. As a result, if we compare \( T \) measured in the far-field for any reported ridge-type aperture structure with circular aperture occupying an equivalent opening area, this translates to less than two orders of magnitude in \( T \) enhancements.

Interestingly, the high \( T \) enhancements were also observed for sub-wavelength apertures surrounded by a Bragg reflector on the metal surface (bull’s eye structure) [9–15]. The concentric corrugations increased the \( T \) power and decreased the beam divergence to \( \sim 10–16^\circ \) solid angle by supporting the standing surface electromagnetic wave with high energy density around the opening [9–11]. In the visible and near-infrared ranges, these surface modes could be the hybrid of ‘real’ and the ‘spoof’ surface plasmons. At longer wavelengths, they are just ‘spoof’ surface plasmon polaritons due to surface corrugation and high metal conductivity at this spectral range [19]. The combination with bow-tie aperture geometry further improved \( T \) efficiency [14, 15]. Up to \( 10^3 \) and \( 10^2 \) enhancements in \( T \) were predicted and measured, respectively [10, 12–15]. Nevertheless, such modest maximum enhancements demonstrated that Bethe’s theory still held very well even for modified sub-wavelength single holes. Exceptions are the aperture arrays ([20] and references therein) and recently reported apertures with inserted...
split ring resonators [21]. However, in the case of single sub-wavelength aperture with Siemens-star geometry microfabricated in an appropriately corrugated screen, we demonstrate below the very high experimental transmission ($T_{\text{star}}$) enhancement, i.e. $T_{\text{star}}/T_{\text{Bethe}} \approx 10^6$, where $T_{\text{Bethe}}$ corresponds to a simple circular aperture of an equivalent opening area (see figure 1). This opens the way for various practical applications such as high-throughput probes for SNOM, facets for VSAL, beam profilers, fibre optic couplers and so on.

2. Experiment

The aperture was microfabricated by focused ion beam (FIB) milling of Al layer deposited on one side of the double-side polished substrate, which was made from high-resistivity single-crystal Si wafer (see figure 2(a)) [22]. Before Al deposition, the Si surface was corrugated by plasma etching with Bragg reflector pattern (see figure 2(b)). Due to the uneven rate of Al etching with FIB, the Si layer between tips had to be also etched away on $\sim 1.6 \mu m$ in order to get the desired structure (see figures 2(e) and (f)). The broadband terahertz (THz) time-domain spectroscopy (TDS) system (Pulse IRS-2000 (AISPEC)) with four off-axis parabolic mirrors in typical optical geometry was used for $T$ measurements of spectra and images. The THz beam was linearly polarized at the focal $XY$-plane and had a numerical aperture of $\sim 0.18$, i.e. the propagating beam had a cone shape with a maximum incident angle of $10.3^\circ$ with respect to the $Z$-axis. The sample was positioned at the $XY$-plane with Si wafer substrate normal to the $Z$-axis (see figure 2(a)) by using an $XYZ$-spatial scanner ($10 \mu m$ minimum step). Waveforms were collected for spectral and image analyses with 65 536 and 8132 data points at $\sim 4.2$ fs time intervals, i.e. with $\sim 3.6$ GHz ($0.12$ cm$^{-1}$) and $\sim 57.9$ GHz ($1.92$ cm$^{-1}$) spectral resolutions, respectively. Measurements were made in ambient (in air) and vacuum conditions as indicated.

Figure 1. Comparison of Bethe’s theoretical and experimental transmissions for our circular/bull’s eye [10, 14] and bow-tie/bull’s eye [12–14] apertures, where $D$ is the incident beam spot diameter.
Figure 2. Schemes and scanning ion microscope (SIM) images of the microfabricated Siemens-star aperture surrounded by Bragg reflector pattern: (a) the scheme of the aperture in Al screen on Si substrate; (b) the geometrical scheme of the Bragg reflector around the aperture; (c) the enlarged side view; (d) the aperture top view; (e) the aperture side view; and (f) the side view of the sector-shaped slit. See text for more details.

In this work, we succeeded in microfabricating a single sub-wavelength aperture (see figure 2) with truly remarkable $T$ enhancements. It was made in Al layer ($\sim$ 4 skin depths at 0.6 THz [23]) deposited on corrugated Si substrate (see figure 2(a)). The Bragg reflector geometry on figure 2(b) was essentially similar to the reported one [14], since it worked well in THz region, but microfabricated differently. The longest-wavelength resonance $T$ maximum, $\lambda_{\text{max}}$, was expected at $\lambda_{\text{max}} \approx L n_{\text{Si}}$, where $L = 132 \mu m$ was the Bragg reflector lattice constant [10]. The aperture itself had a unique structure of sector-shaped slits between converging Al tips (see figure 2(c)). These tips had apex radii, $r$, of $\sim$ 200 nm with $\sim$ 1 $\mu m$ separation distance, $2r$, for opposite ones at the centre of the structure (see figures 2(d) and (e)). Such a Siemens-star aperture was designed to achieve high $E$ enhancements at its centre. This was expected from extremely high $E$ enhancements predicted theoretically for star-like arrangements of multiple metal prolate spheroids forming nanolens [24]. At THz frequencies, the $E$ amplitude should be enhanced around opposite aperture tips via the nonresonant lighting rod effect [25, 26].
Figure 3. Transmission THz spectra of the Siemens-star aperture surrounded by Bragg reflector pattern in ambient and vacuum conditions (see the illumination scheme in figure 2(a)). The blue colour spectrum (a.u.) was obtained from fast Fourier transform of the waveform limited by the round trip time of pulses reflected inside Si substrate. The THz transmission spectrum of Si substrate is also shown for comparison. The lime green spectrum corresponds to the illumination geometry shown in the inset (see the text for more details). With the aperture (or wafers) removed, the intensity of the transmitted THz source radiation was used for reference spectra.

This enhancement has a pure geometric origin. On a rough conductor, $E$ is largest near the sharpest surface feature and its enhancement factors could reach up to $\sim 10^3$ for high-aspect-ratio conical nanowires [27]. For example, this well-known effect is utilized in scattering-type apertureless near-field optical microscopy/spectroscopy. Typically, the confinement of the enhanced $E$ should be within a distance of several apex radii [28, 29]. Thus, converging Al spokes should increase $E$ collectively, especially for radially polarized illumination (see figure 2(c)). In addition, very high $E$ enhancements were expected inside narrow sector-shaped slits [30, 31]. Consequently, the light should be transmitted (scattered, $\propto E^2$) more effectively through such an aperture compared to the one with smoother boundaries. Recently, we had also demonstrated extremely high transmission efficiency for the array of apertures having a similar pointed-shape geometry, although the main transmission mechanisms for a single aperture and aperture arrays are different [32, 33]. In addition, the aperture eightfold rotational symmetry was used to minimize the possibility of polarization-dependent transmission due to rotation misalignments in the XY-plane between the aperture tip and incident $E$ polarization directions.

Figure 3 shows the $T$ spectrum of our aperture which was placed at the focal plane and positioned at this XY-plane for maximum $T$. Note that it was modified by multiple Fresnel reflections of incoming waves inside plane-parallel Si substrate (a kind of low-finesse Fabry–Perot etalon, see figure 4). This was manifested by the appearance of interference fringes on resonance $T$ bands, whose spectral positions, $\nu$, were well described by the Airy function:

$$T = T_1 T_2 \left\{ \left( 1 - \sqrt{R_1 R_2} \right)^2 + 4 \sqrt{R_1 R_2} \sin^2 \left[ 2\pi \nu n_{Si,l} \cos(\theta) / c + (\Delta \phi_1 + \Delta \phi_2) / 2 \right] \right\},$$

(2)
where $c$ is the speed of light and $T_1$, $R_1$, $\Delta \phi_1$ and $T_2$, $R_2$, $\Delta \phi_2$ are the transmittances, reflectances and phase changes at the first and second reflectors within resonator having refractive index $n_{\text{Si}}$, length $l$ and angle of refraction $\theta$, accordingly. At THz frequencies, the $T$ at fringe maxima are $\sim 100\%$ for Si substrate itself since its absorptivity is very small for $380 \, \mu\text{m}$ wafer thickness (see figure 3; [32]). As expected, $\lambda_{\text{max}} \approx L n_{\text{Si}}$ (see the spectrum shown in blue on figure 3). This proved that $\lambda_{\text{max}}$ could be fine-tuned by substrate design and its optical properties.

The weak amplitude of the $E$ oscillations between $\sim 4$ and $\sim 11 \, \text{ps}$ in the aperture transmitted waveform (see figure 4) indicates that the fraction of the field radiated directly from the aperture is much higher than the fraction of time-delayed fields propagated and radiated on periodically spaced grooves away from the hole. In other words, the radiation spot on the exit surface is highly spatially confined just at the aperture opening. Otherwise, more pronounced one-to-one correspondence between the number of surface grooves and the number of temporal damped oscillations should be observed [34].

Remarkably, the maximum aperture $T_{\text{star}}$ measured in far-field reached $\sim 3\%$ at $\sim 0.64 \, \text{THz}$ ($\lambda_{\text{max}} \approx 470 \, \mu\text{m}$). To demonstrate the large magnitude of this value more clearly, the same aperture was scanned in the focal $XY$-plane of the THz beam to measure its $T$ at each mapped position. The resulting high-resolution images of the focal spot size and the shape of THz beam are shown in figure 5. For comparison, the red dot in figure 5(a) indicates the relative size of circular aperture with $R_a = 25 \, \mu\text{m}$ to the focal spot dimensions. Figure 5(a) is the image in the time domain and figures 5(b)–(d) are images in the frequency domain. As seen from figure 5, the THz beam focal spot size and shape depend on observation frequency. Two symmetrical lobes of electric field distribution were due to the linear polarization of the focused beam [35, 36] and the dipole nature of the THz source. One should also note the quality and simplicity of the THz beam profiling with our sub-wavelength pinhole compared to electro-optics detection [37], detector scanning [38] or the sharp knife edge method [39]. As a result, the $T_{\text{star}}/T_{\text{Bethe}}$ enhancement factor at $\lambda = \lambda_{\text{max}}$ could be estimated as follows:

$$\frac{T_{\text{star}}}{T_{\text{Bethe}}} \approx \frac{(0.03/2) \cdot 27 \pi^2 S_{\text{beam}}}{64 S_a (k \cdot r_a)^4} \approx \frac{0.03 \times 243}{4096 \left[ R_a^2 - \varphi \left( R_a^2 - r_a^2 \right)^2 / 45^2 \right]} \frac{\lambda_{\text{max}}^6}{r_a^4} \approx 10^6. \quad (3)$$

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Figure 5. Electric field distributions in the focal plane of a linearly polarized THz beam: (a) intensity image measured around the maximum of the time-domain wave forms for THz pulses transmitted through the aperture (see figure 4); (b)–(d) transmission images in the frequency domain. With the aperture removed, the intensity of THz source radiation transmitted in ambient conditions was used for the reference spectrum. The spatial scanning was performed with 20 µm steps. See text for more details.

In the above expression, the sector-shaped slits occupy area 
\[ S_a \approx \frac{\pi}{360} \left( R_a^2 - 8\varphi(R_a^2 - r^2) \right), \]
where \( R_a \approx 25 \mu m, \ r \approx 0.5 \mu m \) and \( \varphi \approx 32^\circ \) (see figure 2). This area could be equalized to the area of circular aperture with effective radius \( r_a \approx 13 \mu m \) (i.e. \( k \cdot r_a \approx 0.17 \) at \( \lambda_{max} \)). From figure 5(c), the experimentally measured \( S_{beam} \approx \pi(3\lambda_{max})^2/2 \). For comparison with \( T_{Bethe} \), \( T_{star} \) was limited to the first transmitted pulse (see figure 4). Due to \( \sim 30\% \) reflectivity at the Si/air interface, each of the three successively transmitted pulses was reduced in amplitude by \( \sim 70\% \). Therefore, the first pulse accounts for \( \sim 1/2 \) from the total aperture transmittance of \( \sim 3\% \) (see figure 3), i.e. \( T_{star} \approx 0.03/2 \) for comparison with \( T_{Bethe} \). Although we cannot measure the angular dependence for \( T_{star} \) with our present THz-TDS apparatuses, previous studies of beam shape for bull’s-eye apertures showed a maximum solid angle divergence of 10–16° [9–11]. Assuming at least a similar divergence for \( T_{star} \), our apparatuses with a light collection cone angle of 10.3° (see section 2) probably captured most of the transmitted light. Thus, our experimental \( T_{star}/T_{Bethe} \) estimate is a conservative one. Here it should be stressed that this result points at very large \( E \) enhancements at the tip apexes and nearby slits. The local heating, plasma generation, nonlinear spectroscopy, optical trapping, etc are interesting topics to study in relation to this finding.

To confirm our results, we also microfabricated the same Siemens-star and simple circular apertures with \( R_a \approx 25 \mu m \) as described in section 2, but without Bragg reflector patterns. In
addition, \( T \) of the circular aperture with \( R_a \approx 25 \mu m \) and identical Bragg reflector geometry was already measured at THz frequencies with a parametric oscillator (a widely tunable coherent THz-wave source) and a 4 K Si bolometer [14]. Its \( T \) is plotted in figure 1 for comparison (see green square). As expected, none of our apertures showed measurable \( T \) with the THz-TDS apparatus (not shown). This is because the expected transmission enhancements due to the Bragg reflector should be between one and two orders of magnitude [9–15]. For apertures without the Bragg reflector, the \( T \) values were below the sensitivity of our THz-TDS (\( T \sim 10^{-3}–10^{-4} \)). Obviously, an aperture with \( R_a = r_s = 13 \mu m \) will also have undetectable \( T \) (not microfabricated). Therefore, these results showed the importance of combined enhancements due to Siemens-star structure and surrounding corrugation.

Generally, it seems that highly enhanced \( T \) for apertures with \( 2R_a/\lambda_{\text{max}} \ll 1 \) will be expected for the following tip geometries: \( 1 \leq r_t \leq 200 \text{ nm} \), \( r_t \leq r \leq 5r_t \), and \( 4 \leq N_t \leq 360^\circ/\varphi \), where \( \varphi = 2 \arcsin[r_t/(r_t + r)] \) and \( N_t \) is the even number of the tips (see figure 2(d)). Regarding annular groove geometry, its influence on resonance lineshape and enhanced transmissions is well described in the literature [16, 34, 40–42]. In our case, the desired number of grooves, \( N_g \), around the central circle with \( 2L \) radius could be defined as follows: \( 4 \leq N_g \leq (D - L)/(2L) \), where \( D \) is the incident beam spot diameter and \( L > R_a \) (see figure 2(b)). If necessary, \( D \) could be expanded appropriately to get at least \( N_g = 4 \) for setting up resonant \( \lambda_{\text{max}} \). The \( N_g > (D - L)/(2L) \) will have little effect on aperture transmission characteristics.

In addition, the total \( T_{\text{star}} \) collected over large temporal windows could be boosted by appropriate recycling of the THz waves reflected back from the Si/Al aperture interface. Even a very simple modification in the aperture illumination scheme by adding a second Si wafer in the light pass increased \( T_{\text{star}} \) by \( \sim 1.5 \) times due to multiple reflections at Si/air interfaces (see the inset in figure 3 and the corresponding spectrum). By fine-tuning of the separation distance, \( l \), between parallel Si and aperture wafers, the Fabry–Perot/Gires–Tournois multilayer resonances with improved finesse were generated. Obviously, more elaborated etalon/interferometer designs could lead to even better \( T_{\text{star}} \) performance.

To validate our experimental findings, the FDTD simulations on several apertures and incident polarization conditions were also conducted as depicted in figure 6. Although the Bragg reflector was not included in the computational modelling (the subject of our future studies), its additional effect on \( |E|^2 \) values should be between one and two orders of magnitude [9–15]. The detailed effects of the metal type, metal thickness, Siemens-star geometry/dimensions, surface roughness and substrate material/geometry are also interesting topics for additional investigations. Nevertheless, from figures 6(a), (c) and (d) it was evident that high \( E \) enhancements and, most important, their occupied areas within aperture opening had the expected high magnitudes and were larger for the eight-tip aperture compared to the two-tip ones (see also figure 6(f)). The decrease in tip separation distance towards the value of five-tip apex radii also had a profound effect on enhancement values (compare figure 6(e) with others).

In addition, even for an aperture with two tips, the decrease in \( \varphi \) angle led to a sizable effect on enhancements (compare figures 6(c) and (d)). By calculating \( \sum((|E|^2/|E_0|^2)/S_a \) values for different apertures on figure 6 and by normalizing them to the corresponding value for the aperture in figure 6(a), the ratios were 1, 0.25, 0.33, 0.2 and 0.006 for apertures in figures 6(a), (c), (d), (e) and (f), respectively. Therefore, even for linearly polarized illumination,
Figure 6. FDTD simulations of electric (\(|E_x|^2, |E_y|^2, |E|^2\)) and magnetic (\(|H|^2\)) field component distributions as well as the Poynting real vector (\(|P_z|^2\)) power flows (see column names) for different aperture geometries and illumination conditions. All values on colour bars are in the logarithmic scale and normalized to source power. The numbers in red indicate the maximum colour bar values. The indexes \(x\) and \(y\) correspond to the horizontal and vertical axes of the plots, respectively. The broadband Gaussian THz source (0.2–2.2 THz) is located behind the figure plane along the \(z\)-axis normal to the \(xy\)-plane. All apertures are etched in a perfect electric conductor (PEC) screen of 0.4 \(\mu\)m thickness. Data are collected at the exit PEC surface and displayed at 0.7 THz. Apertures in rows (a)–(e) have \(R_a = 25\ \mu\)m, \(r_t = 200\ \text{nm}\), and \(2r = 1\ \mu\)m (except in row (e)). In row (e), the bow-tie aperture with \(2r = 6\ \mu\)m is shown for comparison (the same as in [14]). The rows (a) and (b) depict our eight-tip apertures with \(\varphi \approx 32^\circ\) (see figure 2(d)). The rows (c)–(e) show two-tip apertures with \(\varphi \approx 32^\circ\) for (c) and 90° for (d) and (e). Except for row (b), the electric field of the source is \(x\)-polarized. For row (b), it is 22.5° with respect to the \(x\)-axis in the \(xy\)-plane. Row (f) is the \(r_s = 13\ \mu\)m hole having an equivalent opening area as in apertures on rows (a) and (b).
the eight-tip Siemens-star aperture (figure 6(a)) was \(3\)–\(5\) times more efficient to generate high \(E\) enhancements in comparison with two-tip ones in figures 6(c), (d), and (e). A more detailed comparison with two-tip apertures will also require far-field simulations of \(E\) angular distribution and actual experimental studies (our future work). The highest \(|E|^2\) values for our Siemens-star aperture were located not only at the very centre of the structure but also in sector-shaped slits. Interestingly, the larger areas of such enhancements were located around the \(y\)-axis pointed tips, which were normal to the polarization direction (see figures 6(a) and 6(b), and 7(a)). This behaviour was also observed for transmission through a large-aspect-ratio rectangular hole [43]. For incident light polarized with \(E\) pointing along the hole’s short axis, huge \(E\) enhancements at both the entrance and exit interfaces of the hole were predicted theoretically. Therefore, by increasing the number of tips in our aperture (i.e. by narrowing the long sector-shaped slits), the aperture performance could be additionally improved. In addition, the Siemens-star aperture demonstrated excellent directivity of \(E\) angular distribution even without a Bragg reflector (see figure 7(b)), which partially confirmed the validity of our experimental \(T_{\text{star}}/T_{\text{Bethe}}\) value.

Although we did not expect and notice experimentally the polarization-dependent transmission for our eight-tip aperture, such an effect was still evident from FDTD simulations (compare figures 6(a) and (b)). In our experiments, the aperture misalignments with respect to the THz beam (slight tilts and rotation) as well as the beam shape (see figure 5) obscured the theoretically predicted polarization dependence. Nevertheless, from FDTD simulations, it was clear that the highest polarization dependence was observed for two-tip structure and that larger numbers of symmetrically arranged tips decreased such an effect. It is also evident from simulations and aperture symmetry that the transmission of multi-tip apertures will benefit from radial polarization.
4. Conclusion

In conclusion, we have demonstrated that an appropriately designed sub-wavelength aperture structure could dramatically increase experimental transmission and make it suitable for practical high-sensitivity/resolution optical applications. Near-field optical probes [14], micro- and nanolenses, photodetectors [44, 45], VSAL [5], chemical sensors [46, 47], beam profilers, optical filters and electro-optic [48] and plasmonic devices [49] are the short list of possible application targets.

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