Metascreen-Based Superdirective Antenna in the Optical Frequency Regime

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A metascreen designed to achieve near-field subwavelength focusing at a given frequency is shown to operate as a superdirective antenna in the vicinity of that frequency at the far field. A metascreen for microwave frequencies based on a simple perfect electrically conducting screen is initially used to explain the principle of operation as a superdirective antenna and to distinguish this operation mode from that resulting in near-field subwavelength focusing. A similar metascreen design based on a silver screen of a finite thickness is then used to demonstrate superdirectivity with nanoantennas in the optical frequency regime.

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Subwavelength focusing and imaging at various portions of the electromagnetic spectrum have received considerable attention over the past several years [1–3]. Achieving those two functionalities necessitates the retention of evanescent field components carrying high spatial resolution information that otherwise decay rapidly. In the near field, these field components can be sustained using carefully formed transmission devices bearing subwavelength features [4,5]. Recently, a simple and intuitive approach for the design of such transmission devices using slotted metallic screens, called metascreens (MSs), was suggested [6]. The design goal of these MSs is to obtain a Gaussian shaped beam of a subwavelength width on a close by measurement plane. Viewing the beam on the measurement plane as a Huygens secondary source, it is clear that as this subwavelength beam becomes narrower, its radiated fields will increasingly resemble those of a small dipole. Hence, it is expected that a MS designed and optimized for near-field subwavelength focusing will exhibit very poor directivity. However, we show here that while this is true for the frequency at which the MS is designed to achieve near-field subwavelength focusing, the MS actually operates as a far-field superdirective antenna array in the vicinity of that frequency. Superdirective antenna arrays consist of elements of almost alternating phase, spaced at subwavelength distances. Superdirective antennas are defined as offering improved directivity compared to ordinary antennas by achieving an angular beamwidth that is narrower than the angular diffraction limit. This limit is defined, for an antenna of a given size, as the beamwidth of an equivalently sized uniformly illuminated aperture [7,8]. The limit is well defined due to the inverse relationship between the aperture size and beamwidth of a uniformly illuminated aperture (see the Supplemental Material [9]). This relationship implies also that there is an aperture size below which the corresponding beamwidth becomes as wide as the entire visible angular range. This aperture size is calculated in the Supplemental Material [9] to be approximately $0.6\lambda_0$ under the full width half maximum beamwidth measure, where $\lambda_0$ is the freespace wavelength. The axial length of all MS arrays described below is smaller than this value. Therefore, they are superdirective, by definition, when their beamwidth is narrower than the entire visible angular range. In recognition of the importance of superdirective antenna array theory, an early effort to apply similar principles in the field of optics was carried out in Ref. [10], where a design of a super-resolving pupil was suggested. Today’s nanoscale manufacturing capabilities have made the creation of optical antennas possible and this field is gaining immense popularity, with a recent increased interest in enhancing the directivity of these antennas [11]. Still, as far as the authors are aware, this Letter is the first to present a simple design of a broadband superdirective antenna array in the optical domain. Aside from the novelty of the specific antenna suggested, the importance of this contribution is in explicitly tying the field of optical antennas design to the well-established theory of superdirective antenna array design [12] and connecting it to a recently suggested design methodology of near-field subwavelength focusing devices [6].

The principle behind the operation of this superdirective antenna is initially explained for the less involved case of a perfect electrically conducting (PEC) MS. The MS was originally designed in Ref. [6] to operate as a near-field subwavelength focusing device at $f_{sat} = 10 \text{ GHz}$. The configuration consists of three slots (see the inset of Fig. 2). The height and width of the central slot are $h_{cen} = 13.2 \text{ mm}$ and $w_{cen} = 1.2 \text{ mm}$, respectively, and those of the satellite slots are $h_{sat} = 17 \text{ mm}$ and $w_{sat} = 0.6 \text{ mm}$, respectively. The distance between slot centers is $d = 3 \text{ mm}$. The screen is illuminated by a normally impinging plane wave with the electric field oriented perpendicular to the broad side of the slots. The following results were obtained using the finite-difference time-domain method as described in detail in Ref. [13] and validated therein.
The slots can be approximated by thin magnetic dipoles since they are narrow compared to the wavelength and surrounded by a PEC screen. For the E-plane radiation pattern, these dipoles can be regarded as infinitesimal with a given dipole moment. A comparison between the dipole moment of the satellite slot, \( M_{\text{sat}} \), and that of the central slot, \( M_{\text{cen}} \), in both magnitude and phase is shown in Fig. 1. It can be seen from the upper panel of this figure that, as initially observed in Ref. [13], the phase difference between the dipole moments of the satellite slot and the central slot is roughly 180° for a rather broad range of frequencies. Moreover, it is evident from a comparison between the two panels of Fig. 1 that the frequency range of opposite phase corresponds to a sweep though all possible values of the dipole moment magnitude ratio. The frequency at which the MS was originally optimized to operate at, \( f_{\text{swf}} \), is within the above frequency range. As explained in the introduction, the optimization of the MS to produce a near-field subwavelength beam at the frequency of operation comes at the price of reduced directivity. Therefore, far-field superdirectivity cannot be achieved at that specific frequency. However, the large range of values that the dipole moment magnitude ratio can attain while keeping the moments 180° out of phase suggests that far-field superdirectivity can be achieved in the vicinity of the screen’s original frequency of operation. Indeed, the plot of the broadside directivity of the MS versus frequency in Fig. 2 exhibits a sharp peak followed by a sharp dip in the frequency of operation at the price of reduced directivity. The other directivity curve in Fig. 2 compares the E-plane radiation pattern of the one-slot configuration, in which the slot width is small compared to the wavelength, is close to omnidirectional at all three frequencies. The E-plane pattern corresponding to the three-slot MS at the original frequency of operation, \( f_{\text{swf}} \), is also close to omnidirectional, as was anticipated in the introduction. The three-slot MS pattern is, however, clearly broadside and end-fire superdirective for the frequencies corresponding to the directivity peak and dip, respectively. The broadside null of the three-slot MS pattern at \( f_{\text{swf}} \) is somewhat shallow due to a slight deviation between the dipole moments of the satellite and central slots of the PEC MS, plotted versus frequency.

A simple analysis of a three element array with varying satellite and central element magnitude ratios and opposite phases yields the following magnitude ratio values for maximum and minimum broadside directivities (see the Supplemental Material [14]):

\[
R_{D_{\text{max}}} = \frac{1 - J_0(2\pi f_{\text{swf}})}{2J_0(2\pi f_{\text{swf}}) - J_0(2\pi f_{\text{swf}}) - 1}, \quad R_{D_{\text{min}}} = \frac{1}{2},
\]

where \( J_0 \) is the Bessel function of the first kind, and \( d \) is the distance between array elements. The dashed curve in the lower panel of Fig. 1 corresponds to \( R_{D_{\text{max}}} \) in Eq. (1). This curve intersects with the curve depicting the true dipole moment magnitude ratio of the MS (the solid curve) at a magnitude ratio of 0.581. This magnitude ratio is obtained at a frequency \( f_{D_{\text{max}}} = 9.851 \) GHz, while a magnitude ratio of 0.5, corresponding to \( R_{D_{\text{max}}} \) in Eq. (1), is obtained at a slightly higher frequency \( f_{D_{\text{max}}} = 9.915 \) GHz. These two frequencies correspond very closely to the frequencies at which the MS directivity curve in Fig. 2 exhibits its peak and dip (see the intersection with the vertical dotted lines). The pattern plots in the left-hand-side panel of Fig. 3 compare the E-plane radiation pattern of the one-slot MS with that of the one-slot configuration for the frequencies \( f_{\text{swf}}, f_{D_{\text{max}}}, \) and \( f_{D_{\text{min}}} \). As can be expected, the E-plane pattern of the one-slot configuration, in which the slot width is small compared to the wavelength, is close to omnidirectional at all three frequencies. The E-plane pattern corresponding to the three-slot MS at the original frequency of operation, \( f_{\text{swf}} \), is also close to omnidirectional, as was anticipated in the introduction. The three-slot MS pattern is, however, clearly broadside and end-fire superdirective for the frequencies corresponding to the directivity peak and dip, respectively. The broadside null of the three-slot MS pattern at \( f_{D_{\text{min}}} \) is somewhat shallow due to a slight deviation.
of the dipole moment phase difference from 180° at that frequency. In the right-hand-side panel of Fig. 3, the pattern plot for the three-slot MS at $f_{D_{\text{max}}}$ is compared with an analytically derived pattern of a three element array with moments of a magnitude ratio and phase difference as obtained from Fig. 1 at $f_{D_{\text{max}}}$. It is evident from this comparison that the MS pattern corresponds very closely to that of the three element array. The lower panel of Fig. 2 depicts the normalized total power radiated from the three-slot MS and the one-slot configuration versus frequency. The total power is normalized at each frequency by the incident power flowing in a screen-free scenario through an area comparable to the slot area in the one-slot configuration. It is apparent from the lower panel of Fig. 2 that the power flowing through the three-slot MS decreases at frequencies corresponding to superdirectivity. However, this tradeoff between directivity and radiated power is partially compensated by the large transmission resonance that peaks at a nearby frequency and pulls the entire power flow curve up for both configurations.

The operation principle explained above holds at the optical frequency range as well. However, other factors such as dissipation, penetration through the screen, and creation of surface plasmon polariton (SPP) waves affect the performance of the antenna. To study those factors, we consider the problem of transmission of a plane wave through a silver screen similar to the one described above, albeit having a finite thickness $T$ and different slot dimensions (see the inset of Fig. 4). The slot dimensions and separation used here were originally obtained in Ref. [15], and later studied further in Ref. [16]. Specifically, the height and width of the central slot are $h_{\text{cen}} = 200$ nm and $w_{\text{cen}} = 40$ nm, respectively, and those of the satellite slots are $h_{\text{sat}} = 130$ nm and $w_{\text{sat}} = 40$ nm, respectively. The distance between the slot centers is $d = 83$ nm. The MS is illuminated by a circular Gaussian beam that is roughly 0.8 $\mu$m full width half maximum at the screen plane. The following results were obtained using the finite-difference time-domain method, with a Drude model based auxiliary differential equation formulation for the silver cells, as described in more detail in Ref. [16] and validated therein.

Figure 4 depicts the directivity and total normalized power entering and exiting the screen versus frequency for a $T = 120$ nm thick MS with three slots as described above, and a screen bearing one wide slot that circumscribes these three slots (see the inset). As for the PEC MS, the directivity plot for the plasmonic MS displays a dip and a peak in the vicinity of the frequency at which the MS operates as a near-field subwavelength focusing device (denoted by an X-shaped marker), while the directivity plot for the circumscribing one-slot configuration is roughly flat. Figure 5 shows two $E$-plane radiation pattern plots for the two sets of frequencies marked by the vertical dotted lines crossing the MS directivity plot in Fig. 4 close to its dip and peak. Again, as for the PEC case, the pattern plots show that the MS exhibits superdirective broadside and end-fire patterns compared with the almost omnidirectional patterns of the circumscribing one-slot configuration, at frequencies close to the directivity peak and dip, respectively. As was done in the PEC case, the total power plots in the plasmonic case, shown in the lower panels of Figs. 4 and 6, are normalized at each frequency by the incident power flowing in a screen-free scenario through an area comparable to the slot area in the one-slot configuration. Again, as for the PEC case, the total power exiting the three-slot MS displays a dip in the vicinity of the frequency of superdirectivity. However, in contrast to the PEC case, where the power that does not exit the screen is completely reflected back, in the plasmonic case, a portion of the power is dissipated in the screen due to its finite
conductivity. This dissipation is manifested as a difference in the total power entering and exiting the screen as plotted in the lower panel of Fig. 4. This difference is largest, compared to the power entering the screen, at frequencies corresponding to superdirectivity and at low frequencies where the conductivity is high.

Penetration through the screen was found to degrade its performance as a superdirective antenna and led to the use of a \( T = 120 \) nm thick screen for the above results instead of the \( T = 40 \) nm thick screen originally suggested in Ref. [15] for subwavelength focusing. To show the effect of penetration on the antenna performance, Fig. 6 depicts the directivity and total normalized power entering the three-slot MS, exiting it, and exiting a solid screen (without slots) versus frequency for three different screen thicknesses. The plots of the power exiting a solid screen are roughly ascending lines due to the decrease in screen conductivity as the frequency increases. It is evident that these lines are limiting the dips in the plots of the power exiting MSs of a corresponding thickness. This limiting is due to power penetration through the screen and is governed by its thickness. As the screen becomes thinner, the limiting lines rise and power penetration interferes with the superdirective functionality. This is also seen via the directivity plots in the upper panel of the figure.

The slots excite weak nonradiative SPP waves that propagate away on the screen surface predominantly in a direction perpendicular to the slots’ axes and can be shown to correspond closely to propagation modes of a metal film in vacuum [17] (see the diagram and field profiles in the insets of Fig. 7). Since a finite screen (6 \( \mu \)m \( \times \) 6 \( \mu \)m in lateral dimensions) was used in the simulations yielding all the above results, they may have been affected by reflections of the SPP waves from the screen edges. To assess the influence of these reflections on the results, Fig. 7 depicts the directivity versus frequency for a \( T = 120 \) nm thick three-slot MS of three different screen lengths in the direction perpendicular to the slots. It is evident from this figure that, while reflection from the screen edges introduces some ringing in the directivity plots, its effect on the performance of the antenna is minor.

It was shown that a three-slot metascreen for near-field subwavelength focusing can also operate as a superdirective antenna in the far field at a different, yet close by, frequency. In the optical regime, power penetrating through the screen and SPP waves reaching the screen edges can degrade the MS performance as a superdirective antenna; however, those effects can be mitigated by tuning the screen dimensions. The MS exhibits a tradeoff between directivity and radiated power. While this is a well-known practical limitation of superdirective arrays stemming from large stored reactive energy, it can be partially compensated for by impedance matching techniques [18]. However, as dissipation in the screen contributes a large portion of the reduced radiated power, it is expected to play a dominant role in limiting the performance of such matching techniques. This work opens up future avenues of research including efficient coupling to near-field sources, design of larger arrays for improved directivity, and application of the arrays for standoff imaging and sensing with resolution better than that achievable under the angular diffraction limit.

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