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Subwavelength Focusing with Reflective Metasurfaces Engineered Using the Concept of Perfect Lens

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Abstract – **It is highly desirable to break the diffraction limit on the resolution of optical devices and achieve subwavelength focusing. Despite numerous solutions that have been developed throughout the years, a practical method to obtain subwavelength focusing without the generation of undesired sidelobes is a challenge to this day. We have developed a feasible strategy to achieve this goal based on the concept of perfect lens. We envisage important practical applications of subwavelength focusing that become possible using this method.**

I. Introduction

Subwavelength focusing is crucial when it comes to enhancing the resolution of imaging systems, increasing the sensitivity of detectors, and realizing numerous high-tech applications including micro/nanoscopy, nanolithography, and optical trapping. Overcoming the diffraction limit, which enables focusing in subwavelength volumes, requires tailoring the evanescent spectrum of field distributions. For wave propagation in air, the evanescent modes, i.e., modes with the transverse wavenumber $k_x > k_0$, exponentially decay away from the source or the imaging object, while the propagation modes ($k_x \leq k_0$) propagate. Therefore, for usual focusing devices, in the far zone only propagation modes contribute to focusing and image creation. One way to overcome this limit is to enhance evanescent-mode fields using some resonant structure positioned enough close to the focal point. In 2000 John Pendry showed that a planar slab of a negative refractive index material can manipulate the near field in such a way that it achieves perfect imaging, i.e., a theoretically perfect reconstruction of the source-plane field distribution in the plane passing the focal point [1]. In a perfect lens, subwavelength focusing is achieved due to resonant excitation of high-amplitude surface waves at the slab surface. Here, we show that it is possible to design an impenetrable reflecting surface that provides the same functionality. In this work, based on our recent results on subwavelength focusing with power flow-conformal metamirrors [2], we use that approach to emulate the field created by a perfect lens. This approach allows theoretically perfect focusing in the absence of any receiving object (energy sink) at the focal point, because the created power flow is continuous power flow: after converging to the focal point, the power flow again diverges into space behind the focus. Indeed, this is the field structure that exists behind a perfect lens formed by a slab of a double-negative material. After constructing the desired field distribution, we use the uniqueness theorem and find the impedance on the reflecting boundary that creates the desired field when illuminated by the incident wave.

II. Subwavelength focusing with perfect lens

We can form the desired distribution of reflected field assuming that the reflected plane wave is generated by a virtual source placed behind the perfect lens formed by a double-negative medium characterized by the refraction index $n = -1$ [see Fig. 1(a)]. The field behind the double-negative perfect lens forms a super-resolution hot spot at the focal point. The power flow of the reflected field is directed away from the reflector, and after passing the focal point, it diverges again as from a virtual point source located at the focal point. In Fig. 1(b), because the amplitude of the virtual source generating the reflected field has been adjusted to satisfy power conservation, the averaged power crossing the surface is zero. However, the required surface impedance is complex-valued (an active/lossy

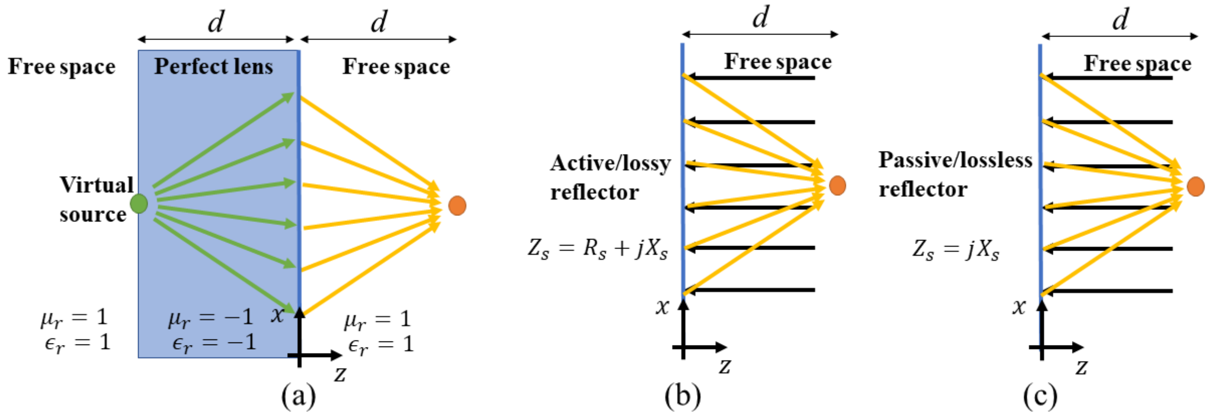


Fig. 1: (a) Virtual source along the perfect lens formed by a double-negative medium slab. Using the total field we can calculate the required surface impedance of the reflector. (b) A flat focusing reflector is implemented by "active/lossy" elements. (c) A flat focusing reflector is implemented by lossless elements.

boundary). Obviously, realization of active surfaces is not practical, and we consider also the case when the real part of the impedance is set to zero, Fig. 1(c).

As an example, we consider a 2D problem of a perfect-lens slab of thickness $d = 0.2\lambda$. The virtual source is a current line I_0 positioned at the lens surface [Fig. 1(a)]. In front of the lens, the virtual source field is a cylindrical wave

$$\mathbf{E}_\mathrm{s} = -\frac{\eta k I_0}{4} H_0^{(2)}(k r_\mathrm{s})\hat{y}, \qquad \mathbf{H}_\mathrm{s} = \frac{j}{\eta k} \nabla \times \mathbf{E}_\mathrm{s}, \tag{1}$$

where η is the free-space impedance, k is the vacuum wavenumber at the operation frequency, I_0 is the amplitude of the source current, $H_0^{(2)}$ is the zero-th order Hankel function of the second kind with $r_\mathrm{s} = |\mathbf{r} - \mathbf{r}_\mathrm{s}| = \sqrt{(x - x_\mathrm{s})^2 + (z - z_\mathrm{s})^2}$ being the distance from the observation point $\mathbf{r} = (x, z)$ to the virtual source location $\mathbf{r}_\mathrm{s} = (x_\mathrm{s}, z_\mathrm{s})$, and $\hat{z}$ is the unit vector in the z direction. The harmonic time dependence in form $e^{j\omega t}$ is assumed. Spatial harmonics in terms of k_x can be found by taking spatial Fourier transform

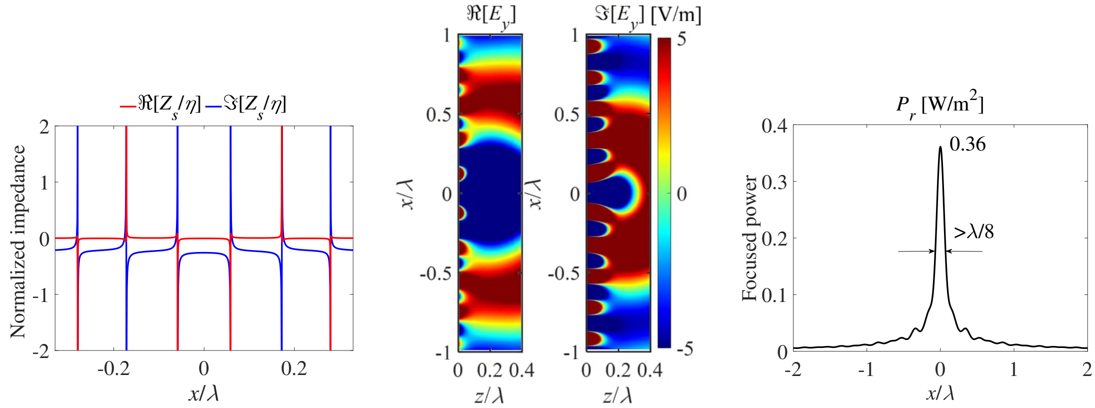
$$\mathscr{F}\{\mathbf{E}_\mathrm{s}\} = -\frac{\eta k I_0}{4} \frac{2}{\sqrt{k^2 - k_x^2}} e^{-j\sqrt{k^2 - k_x^2}|z|}, \quad \mathrm{Im}[\sqrt{k^2 - k_x^2}] < 0. \tag{2}$$

Behind the lens, the virtual source fields are as desired reflected fields, perfectly focused at $z = d$. We calculate these fields by integrating their spatial harmonics using inverse Fourier transform. If we define a flat surface as the reflector plane, the required surface impedance is found as

$$\mathbf{E}_\mathrm{t} = Z_s \hat{n} \times \mathbf{H}_\mathrm{t}, \tag{3}$$

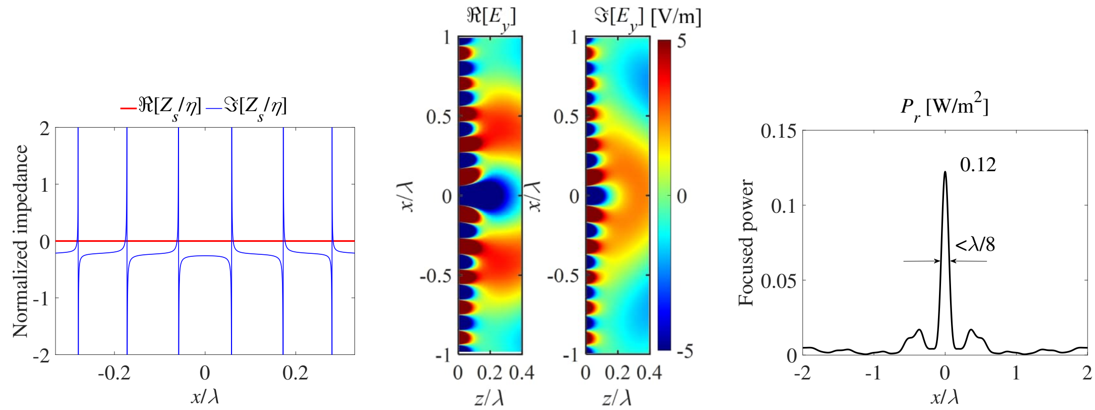
where $\mathbf{E}_\mathrm{t}$ and $\mathbf{H}_\mathrm{t}$ are the total electric and magnetic fields ($\mathbf{E}_\mathrm{t}$ has only a z-component), $\hat{n}$ is the normal unit vector pointing towards the incident wave source. The total fields are the sums of the incident field and the field created by the virtual source. We can define a flat surface located at $z = 0$, and calculate the required surface impedance using Eq. (3), for subwavelength focusing at $z = 0.2\lambda$ and $x = 0$. The found surface impedance shown in Fig. 2(a) is complex-valued whose real part takes both positive and negative values, meaning that the metasurface is active/lossy. The amplitude of electric fields reflected from the flat active/lossy surface is plotted in Fig. 2(b). The absolute value of the reflected power $P_r = \frac{1}{2\eta}|E_r|^2$ [W/m^2] from the metamirror is shown in Fig. 2(b). The hot-spot size is a bit larger than $\lambda/8$.

A simple way to avoid active/lossy elements is to force the real part of the surface impedance to be zero and keep the imaginary part unchanged. Figure 3(a) shows the surface impedance of the corresponding flat lossless metasurface, and Fig. 3(b) shows the reflected electric fields. The fields are different from the active/lossy case (see Fig. 2) because we do not allow energy to pass the reflecting boundary at any point. The absolute value of the reflected power is shown in Fig. 3(c). Compared to the active/lossy case focused power has declined, but the hotspot size is even smaller.



(a) (b) (c)

Fig. 2: Active/lossy metasurface: (a) normalized surface impedance, (b) electric fields, and (c) absolute value of the focused power along the focal line $z = d$. The amplitude of the virtual source $I_0 = 0.48$ mA.



(a) (b) (c)

Fig. 3: Lossless metasurface: (a) normalized surface impedance, (b) electric fields, and (c) distribution of the absolute value of focused power along the focal line $z = d$.

III. Conclusion

Based on the concept of perfect lens and the power flow-conformal approach to design metasurface reflectors, we have established a method to engineer metasurfaces for subwavelength focusing of electromagnetic waves. In addition to a flat active/lossy design, we have introduced a lossless metasurface that achieves subwavelength focusing with a hot-spot size $BW = \lambda/8$. Various realizations of low-loss impedance boundaries are possible, for example, as metal corrugated surfaces. Finally, we note that this subwavelength focusing effect is a resonant phenomenon, and it is important to mitigate losses as much as possible. We hope that the results of this work can be used in various applications that require subwavelength focusing.

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