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An analytical investigation of near-field plates

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Abstract

This paper describes an analytical approach to modeling near-field plates, which are non-periodic grating-like structures that can focus electromagnetic waves to subwavelength dimensions. The analysis provides additional insight into the operation and design of such plates that focus cylindrical waves to subwavelength resolutions. Explicit expressions for the current density induced on the plate and its impedance profile are derived. The analytical expressions are validated numerically.

PACS: 41.20.Jb; 42.25.Fx; 42.79.DjNear-field; Evanescent waves; Focusing; Diffraction limit; Metamaterials

1. Introduction

In the past few years, there has been considerable interest in near-field superlenses that can focus electromagnetic waves to subwavelength resolutions. Following John Pendry's work on the "perfect lens" [1], various superlenses consisting of slabs with negative material parameters have been developed and experimentally verified at microwave, infrared and optical frequencies [2–5]. More recently, an alternative approach to subwavelength focusing using patterned, grating-like surfaces was introduced and developed [6,7]. The proposed surfaces have been referred to as near-field plates. A near-field plate is a subwavelength-structured, planar device that can focus electromagnetic radiation from a source to subwavelength resolutions. The plate's textured surface (modulated reactance) sets up a highly oscillatory electromagnetic field that converges to a prescribed focal plane in the plate's near field.

At microwave frequencies, these plates can be realized as non-periodic arrays of reactive elements, while at optical frequencies, nano-fabricated plates consisting of plasmonic and dielectric materials are envisioned [8–10]. Recent experiments at microwave frequencies have verified a near-field plate's ability to focus electromagnetic waves to subwavelength resolutions [11]. In Ref. [11], an experimental near-field plate consisting of an array of interdigitated capacitors was shown to focus 1.027 GHz microwave radiation emanating from an *S*-polarized cylindrical source to a focus with full width at half maximum, FWHM = $\lambda_\circ/18$, where $\lambda_\circ$ is the free space wavelength. Recently, a similar approach to subwavelength focusing has been pursued using holography-inspired screens and spatially beam-shifted transmission screens [12,13].

Previous works have characterized near-field plates in simulation and in experiment [7,11,14–16], while this paper characterizes them analytically. The analytical investigation that follows provides added insight into the operation and design of near-field plates over the numerical design approach described earlier. Closed-form

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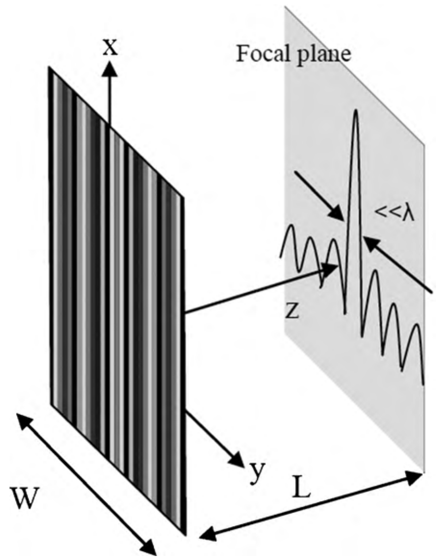

Fig. 1. A schematic showing the near-field plate ($z = 0$) and focal plane ($z = L$). A near-field plate is a non-periodically patterned, planar structure that can focus electromagnetic radiation to lines or spots of arbitrary subwavelength dimension.

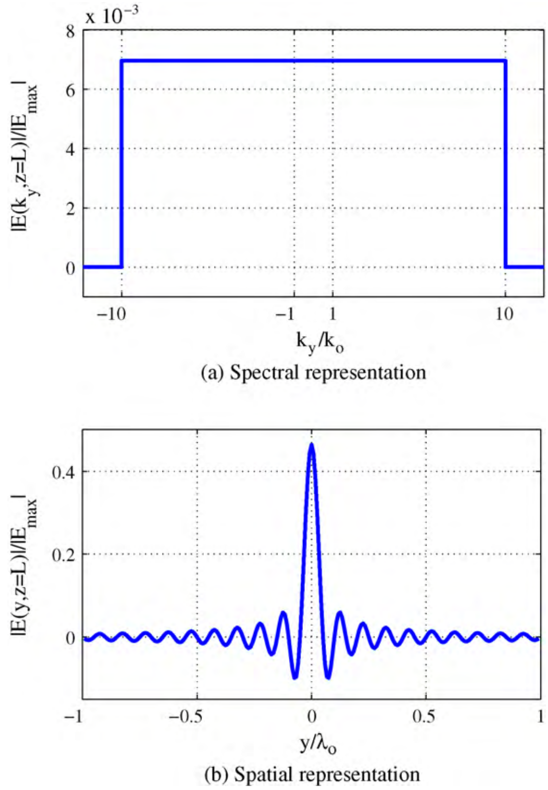

Fig. 2. Spectral and spatial representation of the focal pattern given by Eq. (1). (a) Spectral representation. (b) Spatial representation.

expressions for the currents excited on the near-field plates, as well as expressions for the plates' impedance profile are derived. In the analytical treatment, the plates are assumed to be infinite in width. The current density on the plate is found in the spectral domain and then inverse Fourier transformed to obtain its spatial dependence, as well as the plate's impedance profile. The analytically derived expressions are compared to those computed numerically for electrically wide plates.

2. Near-field plates for *S*-polarized radiation

Fig. 1 depicts the near-field plate configuration considered in this paper. The plate is located along the $z = 0$ plane (sheet plane) and the focal plane is assumed to be the $z = L$ plane, where L is the focal length. Furthermore, the electromagnetic fields are assumed to be polarized and invariant in the x direction (s-polarized). In the discussion, the electric field along the focal plane will be referred to as the focal pattern, while the electric field along the surface of the plate will be referred to as E_{total}. We will investigate a near-field plate that produces a subwavelength focal pattern of the following form,

$$\vec{\mathbf{E}}(y, z = L) = jM|E_{\max}|e^{-q_\circ L}q_\circ L\operatorname{sinc}(q_\circ y)\hat{x} \qquad (1)$$

where $L = \lambda_\circ/16$, $q_\circ = 10k_\circ$ and $k_\circ$ is the free space wavenumber at the operating frequency $f_\circ = 1\,GHz$. Also $M = 6$ is a real constant known as the amplification factor, which expresses focal pattern in terms of the maximum of the incident wave at the surface of the plate: $|E_{\max}| = |E_{\text{inc}}(y = 0)|$. These values for L, $q_\circ$, $f_\circ$, and M are assumed throughout the paper. As explained in Ref. [7], the imaginary number j ensures that the plate's surface impedance is primarily reactive. A near-field plate that produces a sinc focal pattern is chosen since such a plate was numerically and experimentally investigated in Refs. [11,14]. For the assumed parameters, the sinc focal pattern and its spectrum are shown in Fig. 2. The constant $q_\circ$ represents the maximum transverse wavenumber $k_y = q_\circ$ that contributes to the focal pattern, and as a result determines its null-to-null beamwidth (BW_{NN}): $BW_{NN} = 2\pi/q_\circ = \lambda_\circ/10$. Finally, the plate is assumed to be electrically thin in the z direction (thickness $\ll \lambda_\circ$) so that current densities in the direction normal to the plate can be neglected, and the plate can be modeled as a sheet with surface impedance $\eta_{\text{sheet}}(y)$ [17].

The first step to designing a near-field plate involves finding the electric field, $E_{\text{total}}(y)$, that is needed at the surface of the plate to produce the focal pattern [7]. By back-propagating the focal pattern given in Eq. (1), $E_{\text{total}}(y)$ can be easily obtained through an inverse