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ScienceDirect

Photonics and Nanostructures – Fundamentals and Applications 13 (2015) 1–7

PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications

www.elsevier.com/locate/photonics

Feature article

Free-space components for microwave transmission ☆

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Received 10 October 2014; received in revised form 18 October 2014; accepted 20 October 2014
Available online 12 November 2014

Abstract

The ability to guide, manipulate, and process radio- and microwave-frequency radiation is limited by two major factors. From a fundamental viewpoint, the intensity and width of a beam propagating in a free space, as well as the angular and range resolution of radar systems, are limited by diffraction. From a practical viewpoint, free-space beam processing is hindered by a lack of free-space instrumentation for beam focusing, steering, or (de)-multiplexing. As a result, modern radar systems often employ advanced signal processing and detection techniques aimed at enhancing target and feature estimation. Here, we propose several new structures founded upon the emerging plasma filament-based approach to metamaterial design that are aimed at addressing such problems and providing tools for greater capability in microwave transmission than has been possible in the past. In particular, we have designed new structures formed from arrays of plasma filaments in air that leverage the anisotropic behavior of such arrays to address the limits of angular and range resolution, as well as the lack of free-space components for processing radiation in wireless communications.

Keywords: Hyperbolic metamaterials; Microwave guiding; Filamentation

When high-intensity femtosecond laser pulses propagate in air, they form one or more plasma filaments [1,2]. At high ($\gg 2 \times 10^9$ W in air) power, arrays of multiple plasma filaments can be observed [3]. The phenomenon of filamentation has attracted great interest in both its fundamental science and applications, which include spectroscopy [4], remote sensing [5–7], triggering of lightning discharges and water condensation in the atmosphere [8–10], and attosecond physics [11,12]. Moreover, various kinds of "photonic lattices" formed out of filaments have been proposed for energy projection and propagation. Specifically, multiple filament-based structures were investigated as possible waveguides for microwave radiation. These include arrays of filaments that are arranged to form air-core metallic or dielectric waveguides, and structures similar to photonic crystal fibers [13–16]. More recently, it was shown that arrays of filaments can be designed to form a highly anisotropic, effective photonic medium that functions as a virtual hyperbolic metamaterial (VHMM) [17]. In preliminary studies, such a medium was designed to counteract diffraction-induced broadening of a continuous microwave beam, and for beam steering in a free space.

Hyperbolic metamaterials are strongly anisotropic media in which the components of dielectric permittivity in orthogonal directions have different signs [18–31]. These structures have gained attention because of their unique physical properties, the most important of which being that their iso-frequency dispersion surfaces are hyperboloids. Therefore, when a beam is incident from

☆ The article belongs to the special section Metamaterials and also is the Feature article selected by the editors of the Journal.

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http://dx.doi.org/10.1016/j.photonics.2014.10.004
1569-4410/

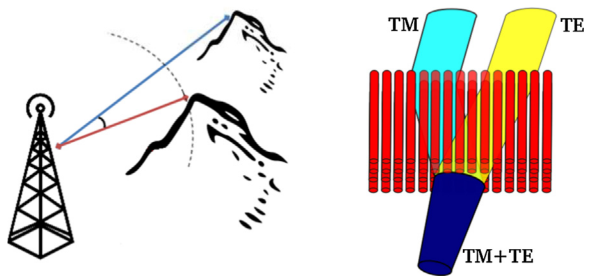

Fig. 1. Schematic of the angular and range resolution problem encountered by microwave radar systems (left), proposed VHHM polarization de-multiplexer (right).

air onto a hyperbolic medium, it can experience negative refraction. Owing to their unique dispersion characteristics, hyperbolic metamaterials can transmit waves with extremely large wavevectors, providing for deep sub-wavelength resolution, while polarization-sensitive negative refraction allows lens-like beam focusing, collimation of diverging beams and polarization-dependent beam steering. Here, we show that the idea of building filament-based VHMMs may enable an entirely new platform for the manipulation of microwave beam and pulses in air, where conventional optical components such as lenses, waveguides or beam (de-)multiplexers are not readily available.

The availability of such free-space microwave components might be of interest in several areas of microwave transmission, as shown in Fig. 1 [32]. First, pulsed microwave radar systems are restricted in their abilities to resolve targets separated from one another in the direction transverse to pulse propagation. This is because when pulses reflected from distinct, but spatially close targets, diffract, they will, at a certain distance, interfere with one another and become nearly impossible to distinguish at the radar receiver; the precision in which a radar system is able to resolve such targets is known as angular resolution. Second, two pulses reflected by targets insufficiently separated in the direction of pulse propagation will interfere, which can cause a receiver to incorrectly interpret the signal as having been reflected from a single, large target; a radar system's resolution in this dimension is known as range resolution. By taking advantage of the unusual properties of hyperbolic media, we have designed a structure able to enhance both of these resolution parameters simultaneously. Finally, we propose a structure that utilizes the anisotropic behavior of VHMM structures to de-multiplex microwave signals in orthogonal polarization states (Fig. 1b), which can be potentially useful in increasing the efficiency of free-space point-to-point communication systems.

One of the most common realizations of hyperbolic media is based on an array of metallic nanorods embedded in dielectric matrix. Such arrays have been shown to exhibit highly anisotropic behavior when the wavelength of incident radiation is much greater than the feature size of the array, such that the structure can be considered as an effective medium [22–24,27]. Under these conditions, the structure can be described analytically by a complex effective dielectric permittivity tensor

$$\tilde{D}(\omega) = \begin{pmatrix} \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{||} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix} \tilde{E}(\omega), \tag{1}$$

where components $\varepsilon_{||}$ and $\varepsilon_{\perp}$ correspond to the two directions of incidence relative to the optical axis of the material and can be calculated using the mixing rule. Such anisotropic materials are characterized by the dispersion relation

$$\frac{k_{||}^2}{\varepsilon_{\perp}} + \frac{k_{\perp}^2}{\varepsilon_{||}} = \frac{\omega^2}{c^2}. \tag{2}$$

Previously, it was shown that a rectangular or circular array of plasma filaments can also exhibit anisotropic behavior as above, in which case the mixing rule equations used to determine the permittivity components of the material take the form [17]

$$\begin{aligned} \varepsilon_{\perp}(\omega) &= \varepsilon_{\mathrm{d}} \frac{(1+f)\varepsilon_{\mathrm{fil}}(\omega) + (1-f)\varepsilon_{\mathrm{d}}}{(1-f)\varepsilon_{\mathrm{fil}}(\omega) + (1+f)\varepsilon_{\mathrm{d}}}\,. \\ \varepsilon_{||}(\omega) &= f\varepsilon_{\mathrm{fil}}(\omega) + (1-f)\varepsilon_{\mathrm{d}} \end{aligned} \tag{3}$$

Here, f is the fill fraction of plasma channels in the filament array given as $f = d_{\mathrm{pl}}/a_{\mathrm{pl}}$, where $d_{\mathrm{pl}} \approx 50-120\ \mu\mathrm{m}$ is the diameter of each filament and $a_{\mathrm{pl}} \approx 450-650\ \mu\mathrm{m}$ is the average distance between filaments in the two dimensional case, ε_{d} is the permittivity of the background dielectric material, which is air in this case [17]. The parameter $\varepsilon_{\mathrm{fil}}$ is the permittivity of each filament, which can be described by the Drude model as

$$\varepsilon_{\mathrm{fil}}(\omega) = 1 - \frac{\omega_{\mathrm{pl}}^2}{\omega^2 + i\omega\nu}, \tag{4}$$

where ν is the frequency of particle collisions given as $\nu = \nu_{\mathrm{ei}} + \nu_{\mathrm{en}}$ (sum of electron-ion and electron-neutral particle collision rates). The plasma frequency term appearing in (4) is given by

$$\omega_{\mathrm{pl}} = \sqrt{\frac{N_{\mathrm{e}}e^2}{\varepsilon_0 m_{\mathrm{e}}}}, \tag{5}$$

where e and m_{e} are the electron charge and mass, respectively, and ε_0 is the permittivity of free space. Finally, the