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Discretely guided electromagnetic effective medium

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A material comprised of an array of subwavelength coaxial waveguides decomposes incident electromagnetic waves into spatially discrete wave components, propagates these components without frequency cutoff, and reassembles them on the far side of the material. The propagation of these wave components is fully controlled by the physical properties of the waveguides and their geometrical distribution in the array. This allows for an exceptional degree of control over the electromagnetic response of this effective medium, with numerous potential applications. With the development of nanoscale subwavelength coaxial waveguides, these applications (including metamaterial functionality) can be enabled in the visible frequency range. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2839320]

Artificial electromagnetic propagation systems comprised of subwavelength elements (waveguides, resonators, etc.) have recently been proposed, studied, and engineered to produce varied, non-naturally occurring combinations of effective electric permittivity ε and magnetic permeability μ, thus, facilitating unconventional methods of controlling electromagnetic radiation.[1–4] Here, subwavelength refers only to waveguide dimensions normal to wave propagation (i.e., not to the longitudinal direction), and means less (usually much less) than half the radiation wavelength, $\lambda/2$. It has been shown that such systems can produce various exotic effects, such as negative refraction,[5] subwavelength lensing[6–8] (i.e., light focusing without diffraction limitation), and cloaking[9–12] (electromagnetic invisibility).

Recently, a *wire guided* effective medium, based on arrays of conducting wires, has been proposed and shown to have a range of interesting properties, such as subwavelength near-field lensing.[13,14] The principle of operation of these systems is based on subwavelength wave guiding through the wire arrays (canalization), similar to that of a multicore coaxial wire.[15] While the electromagnetic response of this medium can be controlled by the array geometry, this control is limited by the *distributed* nature of the wave propagation in (and around) the array. Each wire can be considered as a waveguide of elementary waves, into which the incoming wave decomposes, but there is substantial crosstalk between these *unshielded* waveguides, severely limiting propagation control.

Here, we propose a *discretely guided medium* based on an array of bona fide coaxial subwavelength waveguides piercing an otherwise nontransparent material. Each coaxial waveguide consists of a wire inside a hollow conducting cylinder, with a dielectric in between, as in the ubiquitous household coax (only smaller in size). A schematic of this medium in various configurations is shown in Fig. 1. Figure 1(a) represents a complex configuration with waveguides of different lengths, each line representing a coaxial waveguide. The dimensions of the waveguides transverse to the propagation direction, as well as the average interwaveguide distance, are smaller than the radiation wavelength λ. Note that in this architecture, wave propagation occurs *only* via the coaxial waveguides and not through the medium in between. The fundamental principle of operation of our discretely guided medium is based on Huygens' principle;[16] an arbitrary wave interacting with a medium can be Fourier decomposed into plane waves. Each plane wave, in turn, excites the subwavelength waveguides of the medium. The excitations propagate along the waveguides and are reradiated on the other side of the medium. The resulting Huygens wavelets reassemble into a plane wave, the propagation of which is controlled by the parameters of the waveguides (their distribution, length, direction, etc., inside the medium).

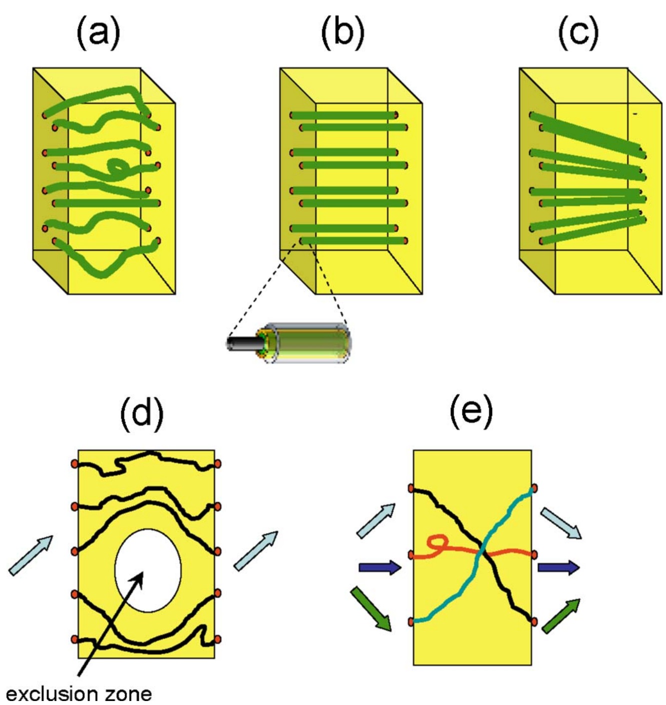

FIG. 1. (Color online) Schematics of guided medium with waveguides of (a) different lengths with same array pattern on each side, (b) equal lengths with same array pattern on each side, and (c) different lengths facilitating scaled (up or down) pattern on each side. An exclusion zone is shown in (d), as example of a cloak, while (e) shows an example of a subwavelength lens. In cases (d) and (e), waveguide paths vary to ensure equal total optical lengths. The inset to (b) sketches a closeup of an individual nanocoaxial waveguide element.

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Each waveguide propagates radiation in a mode identical to or closely resembling an acoustic transverse electromagnetic (TEM) mode, familiar from the common coaxial cable[15,17,18] long used in radio technology. At higher frequencies, the dimensions of the coaxial waveguides must be reduced to accommodate the subwavelength limit, and so in the optical range, nanoscopically small coaxial waveguides (nanocoax) must be used. Such nanocoaxes have been recently fabricated[19] and shown[19–21] to propagate plasmon polaritons which, for frequencies sufficiently below the constituent metal plasma frequency(ies), closely resemble conventional TEM waveguide modes. Coupling of radiation to the nanocoax arrays is envisioned via antenna couplers. Recently, it has been demonstrated[22,23] that nanoantennas can process visible light much like conventional radio antennas process radio waves. The coupling efficiency can be calculated (or computer simulated) at radio frequencies, using standard radio engineering techniques.[18] The same is possible for visible frequencies, taking into account the complete dielectric response of the materials involved.

Consider a simple guided medium with subwavelength coaxial waveguides (and interwaveguide medium) made of "good" metallic conductors (i.e., with low loss and large negative dielectric constant in the frequency of interest) and the interelectrode space (inside the waveguides) filled with a low loss dielectric. These conditions, easy to assure in the radio frequency range, can also be achieved in the optical range. In Fig. 1(b), we assume that all coaxial waveguides (one is shown in the inset) are of equal length and their ends form the same periodic arrangement on both sides of the medium. It is straightforward to conclude that any electromagnetic field pattern generated at one surface of this medium is transferred to other side with *subwavelength* resolution. This is because the transfer is achieved by *propagating* TEM-like modes of the subwavelength waveguides. Such modes do not experience frequency cutoff and, therefore, the resolution will be limited *only* by the geometric parameters of the waveguide ends (diameter, areal density). This is in contrast to the case of a conventional translucent material, which is diffraction limited, since the large momentum Fourier components turn into evanescent waves.

Near-field lensing of the field intensity patterns projected onto the surface of the medium is enabled by employing the converging (or diverging) configuration depicted in Fig. 1(c), i.e., with patterns of waveguide ends having different separations on each side of the medium. With nanoscopic waveguides, such a subwavelength lens may be used to increase resolution of conventional optical photolithography, or to improve near-field scanning optical microscopy.

We next consider the far-field response of this medium, which can be computed, in general, for any distribution of waveguides and corresponding couplers on the emitting side. The problem is essentially that of a planar phased array.[24,25] For a system of radiators with inter-radiator distance much less than λ, the far-field response can be estimated. It can be shown[24] that if the lengths of the subwavelength waveguides l_{ij} are chosen so that $l_{ij}\sqrt{\varepsilon_{ij}}=(\hat{n}_1-\hat{n}_0)\mathbf{R}_{ij}+constant$, (where $\mathbf{R}_{ij}$ is the vector position of waveguide (i,j) in the square array and ε_{ij} is its interelectrode dielectric constant), the reradiated far field on the far side, in response to the incoming plane wave in the $\hat{n}_0$ direction, is a simple plane wave propagating in a chosen direction $\hat{n}_1$. Here, (i,j) refers to the spatial coordinates of the waveguide in the plane of the array.

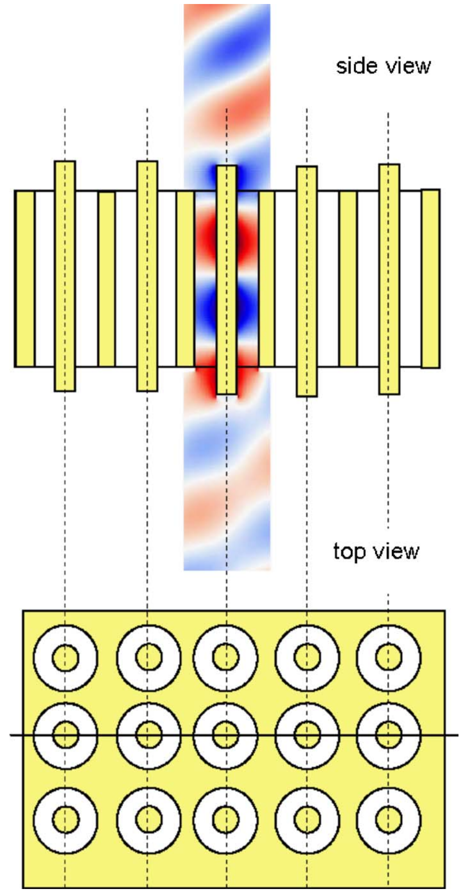

FIG. 2. (Color online) FDTD simulation of the transmission of light (λ=500 nm) through a simple nanocoax medium. Film thickness is 800 nm, array period is 400 nm, diameter of the inner core of the nanocoax is 100 nm, and the inner diameter of the outer electrode is 300 nm. At bottom is a top view.

The significance of this equation lies in the realization that the propagation of an arbitrary incident wave through the medium can now be *fully* controlled.

According to above, a medium with equal length coaxes, as in Fig. 1(b), each filled with the same dielectric, assures that $\hat{n}_1=\hat{n}_0$. In Fig. 2, we show this explicitly via simulation of a square array of straight, parallel nanocoaxes, employing a three-dimensional finite-difference time-domain (FDTD) method to solve numerically Maxwell's equations (for details, see Ref. 26). The metal regions are chosen to be Al, described by the Drude dielectric function, and the interelectrode dielectric is air. The instantaneous electric field magnitude around and inside the nanocoax structure, generated by an incoming plane wave along the direction shown, is encoded as a color map (red to blue is a change of sign, with color intensity proportional to electric field strength). For clarity, only the field distribution in a small vertical strip through one lattice period is shown. Note that the wave emerging below the film is in the same direction as the incident, as expected. The transmission efficiency (~90%) is controlled by the geometry of the structure, including the length of the inner core protrusions (nanoantennas). The transmission is via a TM_{00} mode, which is cutoff free, and which at low frequencies reduces to the TEM mode of the conventional coaxial waveguide.[21]

The exceptional control over wave propagation offered by this guided medium can be used for various applications.

The dielectric constant ε_{mn} can be altered electronically (by employing piezoelectric dielectrics or active components inside the coaxial waveguide), controlling not only the propagation direction, but the wave polarization, phase, amplitude, and frequency. Moreover, antenna-waveguide impedance mismatch and metallic losses along waveguides could be eliminated using amplifiers, mounted directly inside the waveguides. Discrete, electronic switching of light propagation can also be accomplished by "shorting" all or a selected group of waveguides with similar active components. Nonlinear optical components will allow for wave mixing and phase conjugation (wavefront reversal).[27] With nanoscopic elements, these could be possible in the visible range.

The discretely guided medium can simulate metamaterial effects as well. For example, electromagnetic "cloaking" of objects placed between the waveguides occurs. This is demonstrated in Fig. 1(d), where the hole in the material between the waveguides forms an "exclusion zone." Since the antenna cross sections can be made much larger than the physical area occupied by the waveguide ends,[18] there is a possibility, in principle, to arrange waveguides so that this exclusion zone is large, limited only by the propagation length of radiation along the individual waveguides. Any object placed inside the zone will be invisible, as its presence does not alter the wave propagation, which occurs entirely through the coaxial waveguides. In Fig. 1(e) is the case of cross-wired waveguides, where the waveguide entrance and exit endpoints are image-reflected about the horizontal (with the ends of the centrally located red line thus unchanged). Thus, this medium acts like a flat lens, in which intralens wave propagation is not diffraction limited. Note that the medium in this form is not capable of a true negative refraction and, therefore, this is not a superlens in the Pendry sense.[6] However, as phase conjugation is possible in our medium, true negative refraction might also be achievable, since these have been shown to be equivalent.[28]

In conclusion, we propose the concept of a guided medium, based on subwavelength coaxial waveguides, which can be engineered to produce a wide range of desired electromagnetic responses. This guided medium decomposes incoming light waves into partial, propagating waveguide modes, which in turn reassemble into propagating waves on the other side of the medium. Since the subwavelength waveguides do not experience frequency cutoff, a light wave is transmitted through the medium without loss of subwavelength resolution. Additional control over propagation in the waveguides can be obtained via active, nonlinear nanocomponents. With nanoscopic, coaxial nanowaveguides, such as have recently been invented,[19] operation of this medium can be extended to the visible frequency range.

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[1] C. Poulton, S. Guenneau, and A. B. Movchan, Phys. Rev. B **69**, 195112 (2004).
[2] G. Bouchitte and S. Felbacq, J. Appl. Math. **66**, 2061 (2006).
[3] A. A. Krokhin, E. Reyes, and L. Gumen, Phys. Rev. B **75**, 045131 (2007).
[4] X. Wang and K. Kempa, Phys. Rev. B **71**, 233101 (2005).
[5] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).
[6] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[7] S. Guenneau, B. Gralak, and J. B. Pendry, Opt. Lett. **30**, 1204 (2005).
[8] B. Wood, J. B. Pendry, and D. P. Tsai, Phys. Rev. B **74**, 115116 (2007).
[9] J. B. Pendry, D. Schurig, and D. R. Smith, Science **312**, 1780 (2006).
[10] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, Science **314**, 977 (2006).
[11] W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, Nat. Photonics **1**, 224 (2007).
[12] F. Zolla, S. Guenneau, A. Nicolet, and J. B. Pendry, Opt. Lett. **32**, 1069 (2007).
[13] P. A. Belov, C. R. Simovski, and P. Ikonen, Phys. Rev. B **71**, 193105 (2005).
[14] G. Shvets, S. Trendafilov, J. B. Pendry, and A. Sarychev, Phys. Rev. Lett. **99**, 053903 (2007).
[15] R. Litwin, *Teoria Pola Elektromagnetycznego* (Wydawnictwo Naukowo Techniczne, Warsaw, 1978).
[16] C. Huygens, *Exercitationes Mathematicae* (Van der Aa, Leiden, 1690).
[17] Siemens & Halske, German Patent No. 28,978 (27 March 1884); N. Tesla, U.S. Patent No. 514,167 (6 February 1894).
[18] D. M. Pozar, *Microwave Engineering*, 3rd edition, (Wiley, New York, 2005).
[19] J. Rybczynski, K. Kempa, Z. P. Huang, R. Jarzebinska, M. Giersig, A. Herczynski, Y. Wang, M. J. Naughton, and Z. F. Ren, Appl. Phys. Lett. **90**, 021104 (2007).
[20] F. I. Baida, A. Belkhir, D. Van Labeke, and O. Lamrous, Phys. Rev. B **74**, 205419 (2006).
[21] Y. Peng, X. Wang, and K. Kempa, Opt. Express **16**, 1758 (2008).
[22] Y. Wang, K. Kempa, B. Kimball, J. B. Carlson, G. Benham, W. Z. Li, T. Kempa, J. Rybczynski, A. Herczynski, and Z. F. Ren, Appl. Phys. Lett. **85**, 2607 (2004).
[23] K. Kempa, J. Rybczynski, Z. Huang, K. Gregorczyk, A. Vidan, B. Kimball, J. Carlson, G. Benham, Y. Wang, A. Herczynski, and Z. Ren, Adv. Mater. (Weinheim, Ger.) **19**, 421 (2007).
[24] B. A. Munk, *Finite Antenna Arrays and FSS* (Wiley, New York, 2003).
[25] M. K. Smit, Electron. Lett. **24**, 385 (1988).
[26] X. Wang and K. Kempa, Phys. Rev. B **71**, 233101 (2005).
[27] Y. Chan, H. R. Fetterman, I. L. Newberg, and S. K. Panaretos, IEEE Trans. Microwave Theory Tech. **46**, 1910 (1998).
[28] S. Maslovski and S. Tretyakov, J. Appl. Phys. **94**, 4241 (2003).