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A Sub-Wavelength, Hollow-Core Waveguiding Network Based on Complementary High and Low Impedance Cladding

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Abstract

The ability to manipulate electromagnetic waves on scales much smaller than the wavelength is of great interest for various applications in device miniaturization, sensing, and nonlinear wave generation. Surface plasmon polaritons provide a natural solution to this problem through localized resonances. Here, we introduce an alternative novel platform to create deeply sub-wavelength hot-spots in periodic arrangements. The localized power is shown to be guided within narrow hollow channels across electromagnetically thick surfaces composed of complementary low/high impedance electric and magnetic dielectrics. We will discuss physical intuitions on the observed localization phenomenon along with some numerical examples.

1 Introduction

Slow-wave waveguides such as dielectric rods and optical fibers are typically surface wave structures, with higher refractive index relative to the surrounding medium. With most of the energy traveling through the dense core, such structures are prone to relatively high losses, compared, e.g., with hollow conducting waveguides. Waveguides with hollow core and with cladding of the Bragg or photonic bandgap type have been investigated since the 1970's [1]. These structures offer a high frequency alternative to hollow conducting waveguides since the cladding can be made fully reflective using the forbidden band of the photonic bandgap medium.

In the present work, we suggest a related configuration that exploits the idea of total transparency provided by the Weston condition [2–4]. We exploit an interleaving network of high ($\mu_r > 1$) and low ($\varepsilon_r > 1$) impedance rods while adhering to the Weston condition $\mu_r = \varepsilon_r$. Hollow channels are then properly introduced at the dielectric interfaces and junctions, as shown in Fig. 1.

The field outside these channels is predominantly electric or magnetic depending on the constituent material, similar to the case of μ near zero (MNZ) and ε near zero (ENZ) materials [5–7], and thus carries lower power density. These rods then serve as cladding for the hollow core. Simulations confirm slow-wave behavior, in line with the localized nature of the fields.

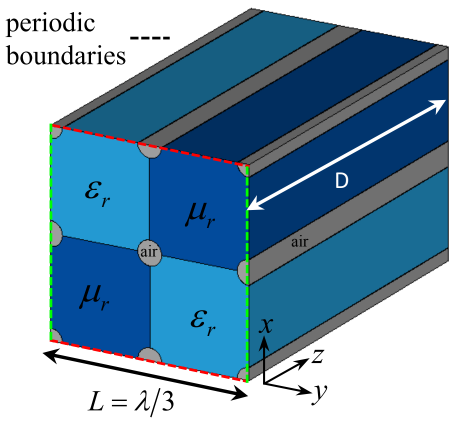

Figure 1. Unit cell of the waveguiding network. Incident wave propagates along z-axis and the power is localized in the cylindrical sub-wavelength hollow (air) cores along this direction. The cladding is made of alternating low and high impedance rods, denoted by ε_r and μ_r, respectively. Under the Weston condition $\mu_r = \varepsilon_r$, the entire incoming power is coupled into the slab without any reflection, and likewise all the power is coupled to free space at the output, without any matching layers.

2 Periodic Array of Hollow Channels

Fig. 1 shows the unit cell of the proposed network of sub-wavelengths, periodic, wave-guiding channels. Four displaced rectangular rods comprise the cladding around the narrow cylindrical hollow core. The rods are alternately magnetic and dielectric materials, see Fig. 1, each one with either $\mu_r > 1$ or $\varepsilon_r > 1$. We also impose the Weston condition $\mu_r = \varepsilon_r$. With this condition, a finite segment of these waveguides does not require additional matching layers to free space, as the effective intrinsic cross section serves as a transparent metasurface, with the added possibility to increase the local density of transmitted power over sub-wavelength hollow cores.

The field inside the rectangular rods is predominantly electric or magnetic. In this sense, the rods behave similarly to μ-near-zero and ε-near-zero materials, with higher confinement associated with higher values of ε_r and μ_r.

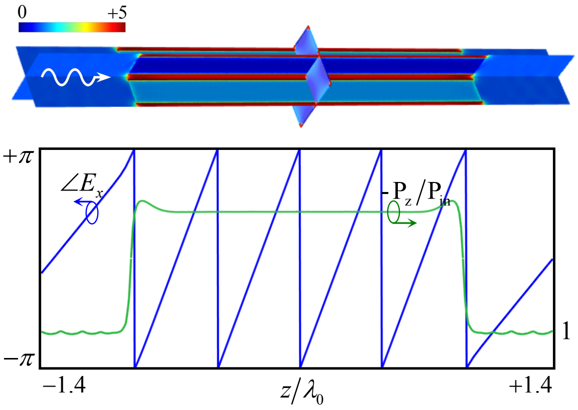

Figure 2. Comsol Multiphysics simulation of the waveguiding network. Top: the power density distribution in the waveguiding structure showing highly confined power density inside in the hollow (air) cores. *D*, as indicated in Fig. 1, is approximately 1.8 times the incident wavelength; bottom: Phase of the electric field (co-pol with the incident wave) and normalized local power in the core center along the propagation path are shown with blue and green lines, respectively.

Power density distribution in the structure as simulated by Comsol Multiphysics is shown at the top of Fig. 2. As predicted, most of the power is localized within the hollow core. The effect is also clear in the cross section as shown in Fig. 3. The fields within the cladding carry significantly less concentration of power, since they consist predominantly either of electric or magnetic components. The incoming wave is fully funneled accompanied by a slow-wave in the hollow core without reflection, as seen from the phase profile along z shown at the bottom of Fig. 2. The slope of the linear phase distribution is higher than that in free space, showing the slow-wave characteristics of the propagating wave in the core. The reflection-free transition from free space occurs over a very narrow region.

3 Conclusion

An important property of the configuration discussed above is its ability to channel the incident wave into the guiding network without any reflection, creating localized concentrated power without the need for any additional matching layers. The same is true for the power that exits at the far end of the structure. This may be modeled as a matched antenna array, radiating for now at broadside. Further investigation into the design of this array, efficiency of coupling into the hollow core, and dispersion would be of interest.

We also envision that single elements of the periodic surface maybe realized, possibly surrounded by dummy elements in a small finite array, as in conventional phased array design. We are currently investigating these aspects along with rigorous modeling of the observed wave confinement.

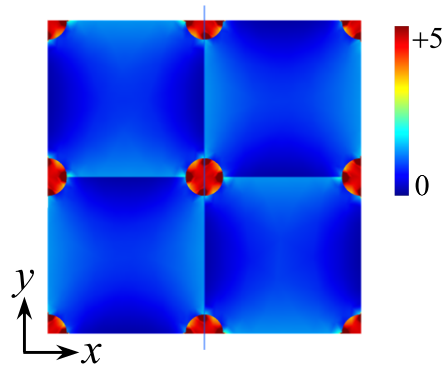

Figure 3. Cross section of unit cell of the waveguiding structure, showing the distribution of power density and its confinement to the hollow core.

4 Acknowledgment

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References

[1] B. Temelkuran, S. D. Hart, G. Benoit, J. D. Joannopoulos and Y. Fink, “Wavelength-scalable hollow optical fibres with large photonic bandgaps for CO_2 laser transmission,” *Nature*, vol. 420, pp. 650–653, 2002.

[2] V. H. Weston, “Theory of Absorbers in Scattering," *IEEE Trans. Antennas Propagat.*, Vol. 11, No. 5, pp. 578–594, 1963.

[3] R. Kastner, “Dispersivity of Balanced Near Zero Permittivity and Permeability (EMNZ) Medium,” *IEEE Trans. Microwave Theory Tech.*, vol. 64, no. 10, 2016.

[4] N. Mohammadi Estakhri, N. Engheta and R. Kastner, “Transparent Metasurface with Prescribed Aperture Field,” *IEEE AP-S International Sympoium*, July 9–14, 2017, submitted.

[5] R. W. Ziolkowski, “Propagation in and scattering from a matched metamaterial having a zero index of refraction.” *Phys. Rev. E*, vol. 70, no. 4, pp. 046608-1 – 046608-12, Oct. 2004.

[6] M. Silveirinha and N. Engheta, “Tunneling of electromagnetic energy through subwavelength channels and bends using e-near- zero materials,” *Phys. Rev. Lett.* vol. 97, pp. 157403-1 – 157403-4, Oct. 2006.

[7] J. S. Marcos, M. Silveirinha, and N. Engheta, “μ-Near-Zero (MNZ) Supercoupling,” *Physical Review B*, vol. 91, 195112, May 11, 2015.