# Trapping the light in a crossed wire mesh: broadband and ultra-subwavelength waveguiding

**T. A. Morgado, J. S. Marcos, M. G. Silveirinha, S. I. Maslovski**

Department of Electrical Engineering, Instituto de Telecomunicações
University of Coimbra, Pólo II, 3030 Coimbra, Portugal
Email: tiago.morgado@co.it.pt, joao.marcos@co.it.pt, mario.silveirinha@co.it.pt, stas@co.it.pt

## Abstract

In this paper we study both theoretically and experimentally the exotic waveguiding properties of ultra-compact metamaterials formed by crossed metallic wires, revealing their superior bandwidth, tolerance to absorption and reduced physical size. In particular, the proposed structured waveguide supports highly confined plasmons with entangled dispersion. The studied waveguide supports such waves over a much wider range of frequencies as compared to other known solutions based on spoof surface plasmons or semiconductor plasmonic-type waveguides.

## 1. Introduction

The advent of nanotechnology has brought with it the demand for devices that may allow confining and guiding electromagnetic radiation in small volumes far beyond the diffraction limit. Most of the proposals are rooted in the excitation of surface plasmon polaritons (SPPs) [1] that occurs at interfaces between materials with oppositely signed permittivities. Such resonant condition is easily met in the optical domain for metal-dielectric interfaces, where the dielectric constant of the metals is predominantly real and negative and thus contrasts with the positive permittivity of dielectrics. However, at lower frequencies metals lose the plasmonic-type response and begin to resemble perfect electric conductors. Hence, an alternative approach is needed to achieve subwavelength confinement and guiding at microwave and terahertz frequencies. One possibility at terahertz frequencies consists in using doped semiconductors (e.g., InSb) instead of metals, since these media exhibit a Drude-type dispersion in this frequency band [2]. However, their practical applications are greatly limited by the effects of losses. Another possibility to mimic the role of SPPs at terahertz or even microwave frequencies relies on structuring metal surfaces. In particular, several works have developed the concept of spoof SPPs [3-8] – geometry-controlled surface waves supported by metal surfaces tailored with subwavelength corrugations. However, these spoof SPPs topologies suffer from an important drawback: the characteristic size of the spoof plasmon waveguides is close to $\lambda / 2$, which contrasts markedly with the ultra-subwavelength sizes of plasmonic wires at optical frequencies. Moreover, even though these structured metal surfaces enable strong field confinement, all of them exhibit a narrowband electromagnetic response.

There are, however, other possibilities to trap and guide the radiation field on subwavelength scale at microwave and terahertz frequencies. Specifically, in a recent series of works [9-10], we have shown that an ultra-compact array of crossed metallic wires has an anomalously strong electric response in the long wavelength limit, owing to the high interaction between the waves propagating in mutually orthogonal sets of wires. In Ref. [10] it was demonstrated that because of such property a grounded metamaterial slab supports strongly confined guided modes. However, such configuration is challenging to fabricate because in such a structure the wave propagates along a direction perpendicular to the planes of wires (propagation along the $y$-direction in Fig. 1a), and also because the wires have to be electrically connected to the ground plane. In order to circumvent this drawback, here we investigate the waveguiding properties of the crossed wire mesh for propagation along a direction parallel to the planes of wires (propagation along the $x$-direction in Fig. 1a). This structure does not require a ground plane.

ISBN 978-952-67611-0-7

## 2. Interlaced plasmons

The geometry of the metamaterial structure is depicted in Fig. 1a. The "double wire medium" considered here can be described using homogenization techniques [10]. In general, such structure is characterized by a strongly spatially dispersive response [10] and consequently supports propagation of additional eigenwaves. Hence, in order to solve the propagation problem analytically, i.e., to calculate the dispersion characteristics of the guided modes supported by the structure, the classical boundary conditions, which impose the continuity of the tangential components of the electromagnetic fields, must be complemented with a set of additional boundary conditions (ABCs) [11]. Specifically, in this case the ABCs are such that guarantee that the microscopic current associated with each wire in the unit cell vanishes at the interfaces [11]. Imposing such boundary conditions, we obtain a homogeneous $8 \times 8$ linear system. The dispersion characteristic of the guided modes supported by the structured material is then obtained by setting the determinant of this linear system equal to zero, and by computing the wave number $k_x$ as function of frequency $\omega$.

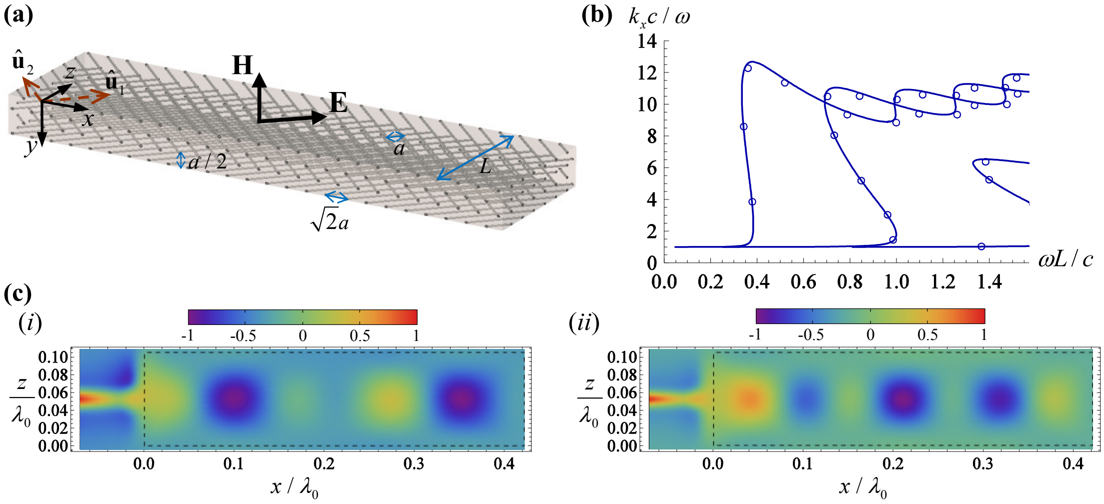

Fig. 1: (a) Geometry of the structured waveguide formed by two orthogonal arrays of nonconnected metallic wires with radius $r_w$. Each array of parallel wires is arranged in a square lattice with lattice constant $a$. One set of wires is oriented along the direction $\hat{\mathbf{u}}_1 = (1,0,1)/\sqrt{2}$, whereas the complementary set is oriented along the direction $\hat{\mathbf{u}}_2 = (-1,0,1)/\sqrt{2}$. The two sets of wires are placed at a distance $a/2$ from each other. The wires are embedded in a dielectric with relative permittivity $\varepsilon_h$. (b) Normalized propagation constant $k_x$ of the interlaced surface plasmons as a function of the normalized frequency. Parameters: $a/L = 0.05$, $r_w = 0.05a$ and $\varepsilon_h = 1$. The solid curves are obtained from the homogenization model, whereas the discrete symbols are obtained with CST Microwave Studio [12]. (c) Time snapshot of normalized $H_y$ at the frequency $f = 1$ GHz for the crossed wires waveguide (*i*) Experimental results; (*ii*) Full-wave results obtained with CST Microwave Studio [12].

Fig. 1b depicts the calculated dispersion characteristic of the guided modes supported by the crossed wires substrate with wires spaced by $a/L = 0.05$. The solid lines in Fig. 1b were computed using the nonlocal homogenization model and follow remarkably well the full-wave results (discrete symbols) calculated with the eigenmode solver of CST Microwave Studio [12]. As seen in Fig. 1b, the considered slab has an exotic dispersion diagram, where the peculiarity of the different branches of the dispersion characteristic being strongly interlaced one with another clearly stands out: a feature not seen in the dispersion diagrams of either dielectric or metal based planar waveguides. The physical origin of such entanglement is simply rooted in the geometry of the structure. In fact, it is a consequence of the strong non-resonant interaction between the two orthogonal arrays of wires. Specifically, each set of parallel wires supports weakly bounded plasmons that strongly interact with the excited plasmons of the complementary set, and hence create these peculiar subwavelength excitations that we designate as "interlaced plasmons".

The dispersion diagram of Fig. 1b shows that the metamaterial slab supports these highly confined interlaced modes (with $k_x c / \omega >> 1$) even when the thickness of the waveguide is deeply subwavelength ($\omega L / c < 1$). This occurs for frequencies larger than $\omega L / c \approx 0.4$ and extends over a wide frequency band. Thus, unlike the spoof SPPs, the interlaced plasmons exhibit, indeed, a truly subwavelength nature and an extremely broadband response. Therefore, the crossed wires waveguide is significantly more robust in terms of bandwidth and reduced physical size than approaches based on spoof SPPs, which makes it a quite interesting solution for subwavelength field confinement and waveguiding at microwave and terahertz frequencies [13]. In addition, it will be shown in this talk that the properties of the interlaced plasmons are nearly unaffected by the loss in metals [13].

In order to further validate these results, we have fabricated a microwave prototype of the crossed wires waveguide using standard printed circuit techniques. The width of the waveguide is $L = 20a = 31.48$ mm, the length along the *x*-direction is $L_x = 4L$, and along the *y*-direction the waveguide is formed by only 4 planes of wires. The cylindrical wires are replaced by strips with width $w_s = 0.25$ mm, and the host dielectric is RT/duroid 5880, characterized by $\varepsilon_h = 2.2$, loss tangent $\delta \approx 0.00065$ and thickness 0.787 mm. The metamaterial waveguide is excited by a small printed dipole antenna, and the *y*-component of the magnetic field was measured using a near-field scanner with a round shielded loop probe scanning along and across the waveguide. It is clear from Fig. 1c(*i*) that, despite the subwavelength dimensions of the waveguide (approximately $\lambda / 10$ along *z*), it supports the propagation of strongly confined guided modes (interlaced plasmons), confirming in this way the results of Fig. 1b. In order to validate the experimental results, we have also simulated the response of the fabricated structure using the electromagnetic solver [12]. The full-wave time snapshot is depicted in Fig. 1c(*ii*), from which one can see that the numerical and experimental results are in good agreement. In the talk, we will present more experimental and numerical results, including some animations, further confirming the guiding and confinement features described above.

## References

[1] S. A. Maier, *Plasmonics: Fundamentals and Applications*, .Springer, New York, 2007.

[2] J. G. Rivas, C. Janke, P. H. Bolivar and H. Kurz, “Transmission of THz radiation through InSb gratings of subwavelength apertures”, *Opt. Express* 13, 847, 2005.

[3] S. A. Maier, S. R. Andrews, L. Martín-Moreno, and F. J. García-Vidal, “Terahertz Surface Plasmon-Polariton Propagation and Focusing on Periodically Corrugated Metal Wires”, *Phys. Rev. Lett.* 97, 176805, 2006.

[4] J. B. Pendry, L. Martín-Moreno, F.J. Garcia-Vidal, “Mimicking Surface Plasmons with Structured Surfaces”, *Science* 305, 847, 2004.

[5] C. R. Williams, S. R. Andrews, S. A Maier, A. I. Fernández-Dominguéz, L. Martín-Moreno and F. J. García-Vidal, “Highly confined guiding of terahertz surface plasmon polartions on structured metal surfaces”, *Nature Photonics* 2, 175, 2008.

[6] A. P. Hibbins, B. R. Evans, J. R. Sambles, “Experimental Verification of Designer Surface Plasmons”, *Science* 308, 670-672, 2005.

[7] S. H. Mousavi, A. B. Khanikaev, B. Neuner III, Y. Avitzour, D. Korobkin, G. Ferro, and G. Shevts, “Highly Confined Hybrid Spoof Surface Plasmons in Ultrathin Metal-Dielectric Heterostructures”, *Phys. Rev. Lett.* 105, 176803, 2010.

[8] M. Navarro-Cía, M. Beruete, S. Agrafiotis, F. Falcone, M. Sorolla, and S. Maier, “Broadband spoof plasmons and subwavelength electromagnetic energy confinement on ultrathin metafilms”, *Opt. Express*, 17, 18184, 2009.

[9] M. G. Silveirinha, C. A. Fernandes, J. R. Costa, “Superlens made of a metamaterial with extreme effective parameters”, *Phys. Rev. B* 78, 195121, 2008.

[10] M. G. Silveirinha and C. A. Fernandes “Nonresonant structured material with extreme effective parameters”, *Phys. Rev. B* 78, 033108, 2008.

[11] M. G. Silveirinha, “Additional boundary conditions for nonconnected wire media”, *New J. Phys.* 11, 113016, 2009.

[12] CST Microwave Studio 2010 (http://www.cst.com).

[13] T. A. Morgado, J. S. Marcos, M. G. Silveirinha, and S. I. Maslovski, “Ultraconfined Interlaced Plasmons”, accepted for publication in *Phys. Rev. Lett.*, 2011.