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Microwire arrays with plasmonic response at microwave frequencies

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We study experimentally the response of three-dimensional arrays of microscopic wires. Very good agreement is found with previous theoretical work indicating that such a system can be considered as an effective plasmonic medium with a specific plasma frequency. The sample size threshold where this effective behavior appears is shown to be relatively small. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1513663]

The electromagnetic properties of parallel wires of a small cross section positioned in a periodic array are currently of great interest. Pendry *et al.* demonstrated that the electromagnetic response of such an array is similar to that of a low-density plasma of very heavy charged particles, with a plasma frequency f_p in the GHz range.[1] Such material can therefore be characterized with an effective permittivity $\varepsilon_{\text{eff}}(f)$ which is negative for frequencies $f<f_p$. Combined with structures producing a negative effective permeability $\mu_{\text{eff}}(f)$,[2] this array can create a metamaterial with negative effective index $n=(\varepsilon_{\text{eff}})^{1/2}(\mu_{\text{eff}})^{1/2}$ and reversed electromagnetic properties over a specific frequency range.[3–5]

The frequency-selective response of arrays of metallic elements has been known in electrical engineering for many years.[6] However, viewing such a system as a plasmonic medium opens new perspectives. In particular, finite bodies made of such a plasmonic medium can support plasmon-polariton resonances characterized by an extremely large scattering cross section.[7] This phenomenon is readily observed at optical frequencies in colloidal nanoparticles;[8] its extension into the microwave range could provide the basis for the realization of subwavelength antennas with outstanding radiation properties.

In Ref. 9 a formula for the plasma frequency of a microwire array was derived

$$(f_p^{\text{theo}})^2=\frac{c^2}{2\pi a^2\ln(a/r)}, \tag{1}$$

where a is the array lattice constant, r the wires radius and c the speed of light in free space.

The objective of this letter is to present experimental studies of arrays with varying geometrical parameters a and r, and compare their responses with Eq. (1). Further, by studying these finite structures, our aim is to determine the size threshold above which a system behaves as a plasmonic medium.

Microwire arrays can be fabricated using lithographic techniques, however the wires do not have a circular section in that case. Further, currently used lithographic substrates have a high permittivity which strongly influences the electromagnetic response of the wires deposited on them. Our objective being the realization of an array of microwires in air, in order to compare with Eq. (1), another fabrication technique was developed.

Low permittivity foam plates are used as substrate (Rohacell HF 51, $\varepsilon=1.07$ at microwave frequencies). Parallel copper wires are deposited on 200×200 mm^2 Rohacell plates at well defined intervals a. In order not to alter the dielectric characteristics of the substrate, the wires cannot be glued or fastened with adhesive film. Therefore a purely mechanical attachment technique was developed, where each wire is clamped in a groove defined in the substrate. For this the Rohacell plate is first cut 0.8 mm deep on a coordinatograph which allows accurate positioning of the groove within (±0.01 mm).

To obtain a plasma behavior, the wires need to be extremely thin and so cannot be applied by hand.[9] A specific tool was therefore fabricated to insert the wires into the grooves [Fig. 1(a)]. It is composed of a small bobbin turbine [A in Fig. 1(a)], where the cooper wire can be rewound. The rewinding is performed with the help of air injection into the turbine (B). The copper wire (C) is then guided into a capillary tube (D) by means of tweezers at one end of the tube and vacuum at the other end. The wire is deposited into the bottom of the groove with the help of a guiding blade (E).

This simple fabrication technique provides great flexibility. It is in particular possible to rapidly realize different wire arrays without the time consuming step of creating a lithographic mask.

Several different arrays have been fabricated using copper wires with radii $r=10$ μm and $r=30$ μm (Elektrisola Ø 0.02 and 0.06 mm). The Rohacell plates have a 4 mm thickness. Additional spacers can be placed between adjacent plates to provide the same wire spacing a between two plates, as within one plate.

In the experiment, several plates with similar wire arrays are placed in an anechoic chamber and the transmission (scattering parameter s_{21}) is measured using horn antennas installed on both sides of the sample and a network analyzer/microwave receiver (HP 8530A), Fig. 1(b). The emitting antenna [A in Fig. 1(b)] generates an electromagnetic field with well defined linear polarization. Two sets of antennas are used to cover the frequency range of our samples: X-band (8–12.4 GHz) and Ku-band (12.4–18 GHz) horn antennas. To avoid scattering from the surroundings, the sample (B) is

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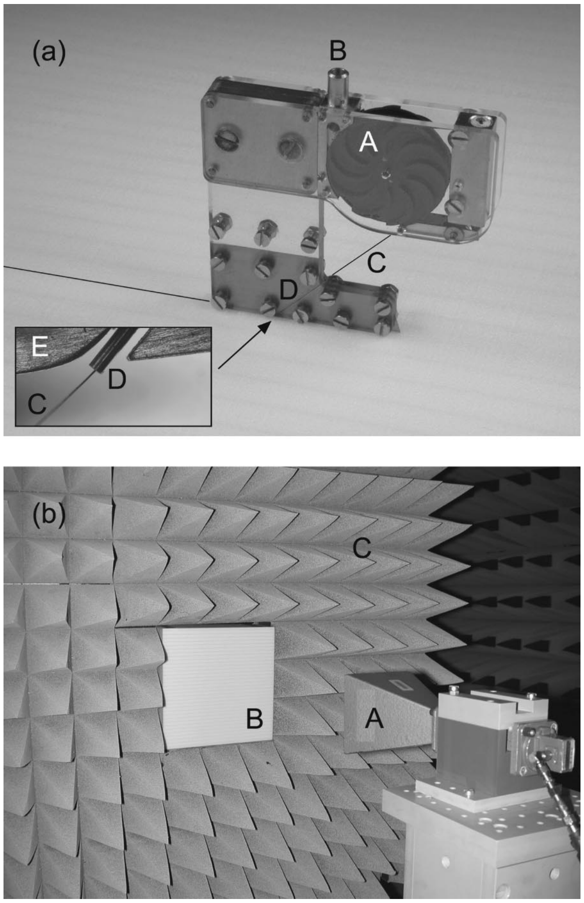

FIG. 1. (a) Tool developed to apply microwires to a Rohacell plate. (b) For the measurement, several Rohacell plates are placed in a window surrounded by microwave absorbing material. The transmission through the sample is measured using horn antennas.

placed in a 200×200 mm^2 window (C) surrounded by microwave absorbing material [Fig. 1(b)].

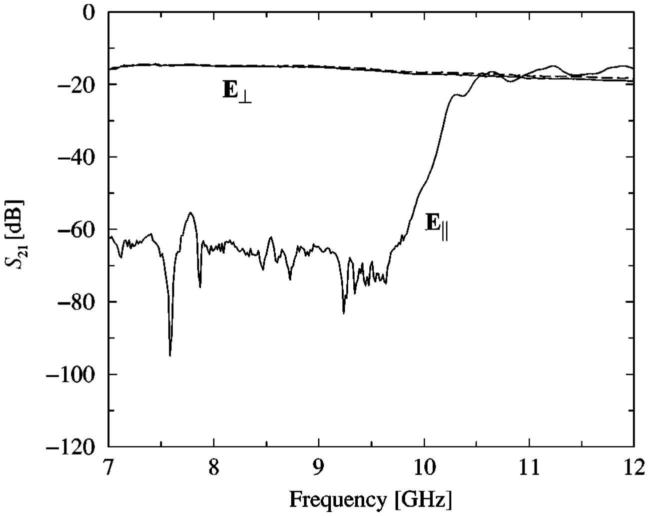

FIG. 2. Scattering parameter for a sample with $r=10\ \mu\mathrm{m}$ and $a=5$ mm (solid lines). Two different incident polarizations $\mathbf{E}_\parallel$ and $\mathbf{E}_\perp$ are considered. The reference measured without sample is also shown (dashed line).

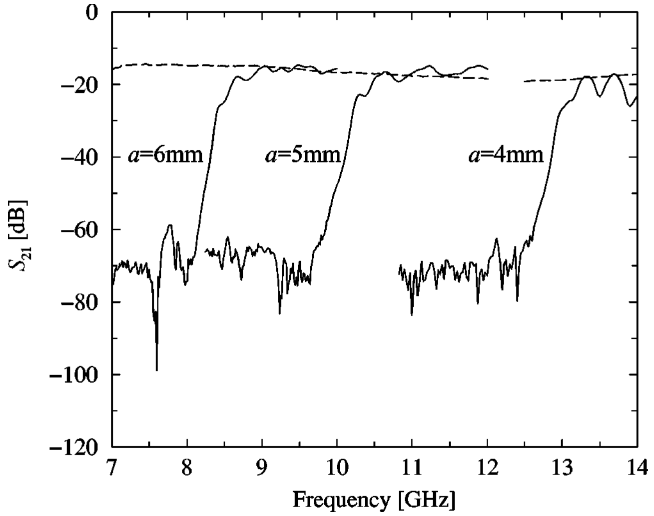

FIG. 3. Scattering parameter s_{21} for three different lattice constants a ($r=10\ \mu\mathrm{m}$). The reference measured without sample is also shown (dashed line).

The first sample considered is an array of $r=10\ \mu\mathrm{m}$ wires with spacing $a=5$ mm. It is composed of 20 Rohacell plates building a 200×200×100 mm^3 parallelepiped. Each plate contains 39 wires. The sample was first placed in the window with the wires parallel to the incident electric field. The corresponding transmission parameter s_{21} is reported in Fig. 2 as a function of the illumination frequency (solid line, $\mathbf{E}_\parallel$). The dashed line in Fig. 2 gives the reference value measured without any sample (empty window). One observes that the wire array behaves like a high-pass filter: at low frequency, the scattering parameter s_{21} is extremely small (less than 60 dB) compared to the reference value of about -15 dB; around 10 GHz, a transition region is observed where s_{21} rapidly goes to the reference value (dashed line); beyond 10.5 GHz, the sample behaves essentially like a transparent material (the fact that the transmission is slightly higher than the reference curve can be attributed to a small focusing effect by the sample).

From the data in Fig. 2, we determine the plasma frequency f_p at the onset of the s_{21} curve to be $f_p=9.8$ GHz, in good agreement with the value obtained from Eq. (1): $f_p^{\mathrm{theo}}=9.6$ GHz. The difference can certainly be explained by the fact that the sample has finite dimensions (about six wavelengths at the resonance frequency).

The sample is then turned by 90° in its plane so that the wires are perpendicular to the incident electric field. In that case the s_{21} values are very close to the reference ones ($\mathbf{E}_\perp$ in Fig. 2): the medium is transparent.

Figure 3 shows the transmission for three different arrays of $r=10\ \mu\mathrm{m}$ wires, with spacing $a=6$ mm, $a=5$ mm and $a=4$ mm, respectively. The latter array, with higher transition frequency, requires the Ku-band set of antennas, which explains the different reference curves (dashed lines in Fig. 3). The measured plasma frequencies are summarized in

TABLE I. Comparison between the measured (f_p) and theoretical (f_p^{theo}) plasma frequencies for different microwire arrays.

r (μm)	a (mm)	f_p (GHz)	f_p^{theo} (GHz)
10	4	12.4	12.2
10	5	9.8	9.6
10	6	8.2	7.9
30	6	9.1	8.7

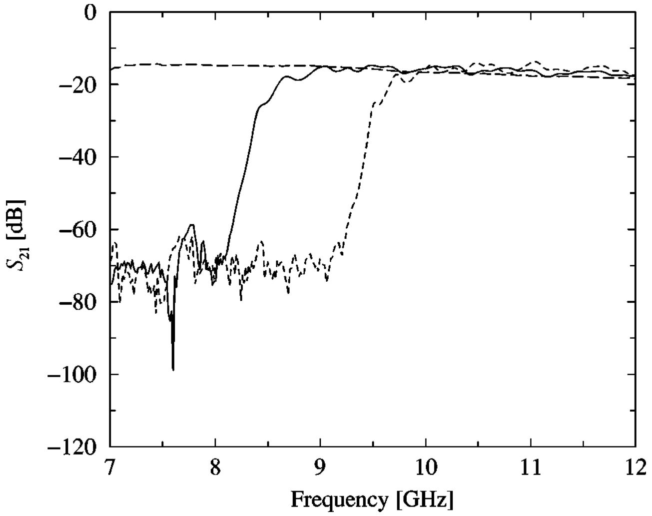

FIG. 4. Scattering parameter s_{21} for two arrays with spacing $a = 6$ mm but different wire radii: $r = 10$ μm (solid line) and $r = 30$ μm (dashed line). The reference without sample is also shown (long-dashed line).

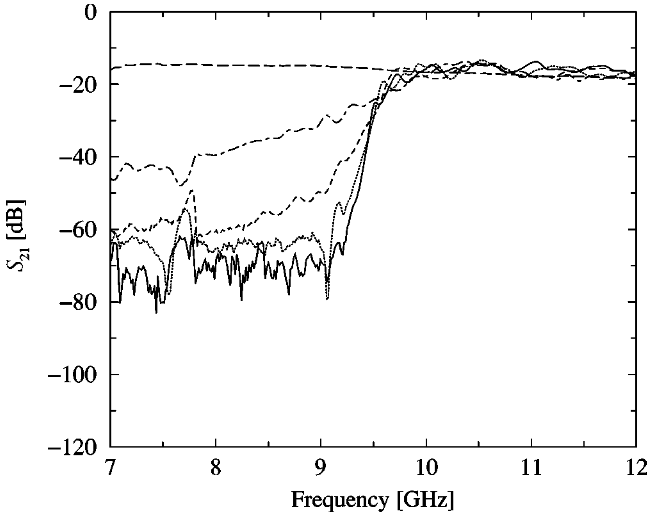

FIG. 5. Scattering parameter s_{21} for samples ($r = 30$ μm, $a = 6$ mm) with an increasing number of plates: 5 plates (dot-dashed line), 10 plates (dashed line), 15 plates (dotted line) and 20 plates (solid line). The reference without sample is also shown (long-dashed line).

Table I. The agreement with the values obtained from Eq. (1) is excellent.

In Fig. 4 we study the other parameter in Eq. (1): the wires radius. Two arrays with spacing $a = 6$ mm and radii 10 or 30 μm are considered. Increasing the wires thickness shifts f_p to higher frequencies, from 8.2 to 9.1 GHz, again in good agreement with Eq. (1) (see Table I).

Finally, the influence of the number of plates is investigated. Figure 5 shows the transmission for samples with 5, 10, 15, and 20 layers of wires, with $r = 30$ μm and $a = 6$ mm. The plasmonic behavior of the sample increases with the number of plates. Already 15 plates provide a sharp transition with very small transmission for frequencies smaller than f_p. Increasing the number of plates to 20 barely influences the response of the sample. It is interesting to note that 15 plates correspond to a sample thickness of four wavelengths at the resonance. This information is important for the practical realization of plasmonic media with a finite size.

To conclude, the simple fabrication technique presented in this letter allows the realization of microwire arrays in air with various lattice constants. We found an excellent agreement between the measured plasma frequency f_p and the formula derived in Ref. 9. Surprisingly, already a relatively small sample, in the order of four wavelengths in size, exhibits such a plasmonic behavior. The control of the plasma frequency in finite sized samples is important for the realization of composite materials with special electromagnetic properties, such as a negative index.

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[1] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, Phys. Rev. Lett. **76**, 4773 (1996).

[2] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).

[3] V. G. Veselago, Sov. Phys. Usp. **10**, 509 (1968).

[4] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).

[5] R. A. Shelby, D. R. Smith, and S. Schultz, Science **292**, 77 (2001).

[6] B. A. Munk, *Frequency Selective Surfaces, Theory and Design* (Wiley, New York, 2000).

[7] J. P. Kottmann, O. J. F. Martin, D. R. Smith, and S. Schultz, Phys. Rev. B **64**, 235402 (2001).

[8] J. J. Mock, M. Barbic, D. R. Smith, D. A. Schultz, and S. Schultz, J. Chem. Phys. **116**, 6755 (2002).

[9] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, J. Phys. C **10**, 4785 (1998).