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SCIENCE DIRECT
Journal of the European Ceramic Society 26 (2006) 2199–2203
www.elsevier.com/locate/jeurceramsoc

CAD of one-layer frequency selected surfaces with metamaterials properties

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Available online 11 November 2005

Abstract

In this study, we present CAD of (a) double slit tetragonal resonators and (b) microstrips (wires) resonators periodically expanded on the top surface of a substrate made from a dielectric, using the finite difference time domain (FDTD) method. From the calculated complex S^*-parameters, we found the effective complex magnetic and dielectric constants of all the structures, when an electromagnetic wave incidents vertically to the top surface of substrate and at two different polarizations of electric field relative to the geometry of resonators. Our calculation shows the existence of positive or negative internal constants and optical bandgaps at different frequency areas between 0 and 60 GHz. Also, in this study, we present a correlation between *S*-parameters and the sign of the calculated internal effective constants.

Keywords: Composites; Dielectric properties; Magnetic properties; Substrates

1. Introduction

Veselago in 1968, reported for first time the existence of very interesting electromagnetic (EM) properties,[1] i.e. negative refractive index (NRI), reversed Cerencov-Vasilov effect, reversed Doppler effect, 'perfect' lens phenomena, etc. to materials with negative magnetic permeability ($\mu < 0$) and dielectric permittivity ($\varepsilon < 0$). Veselago named them left-handed materials (LHM) because in these materials the vectors $\vec{E}$, $\vec{H}$ and $\vec{k}$ form a left-handed triplet, when EM wave propagates through them. The interest in Veselago's work renewed when Pendry et al. in 1999 proposed an artificial material, made from double slit-ring resonators (SRR) with periodic structure along *x*, *y* and *z*-axis.[2] This structure showed a frequency area of magnetic permeability, which was not expected as the structure did not include magnetic materials. In this study, no correlation of internal constants with possible optical bandgaps was presented. In 2000, Smith et al. developed a structure of double SRR (responsible for $\mu < 0$) and Wires (responsible for $\varepsilon < 0$) located in alternating layers.[3] This extension of properties of artificial materials by engineering created a new family of materials named "metamaterials". After these initial publications many metamaterials with NRI properties, sometimes called double negative metamaterials (DNG), have been published.[4] The main characteristic of all of them is a common pass band frequency in which both magnetic permeability and dielectric permittivity are negative.

In this study, we treat the two "traditional" periodic structures which are responsible for the negative internal constants[4] (double SRR and Wires-microstrips) on the top of a dielectric substrate. The substrate, we used in our analysis is a composite forsterite-based material, which shows good characteristics, like real relative dielectric constant $\varepsilon' = 11$, loss tangent $\tan\delta = 0.00008$, real relative magnetic constant $\mu' = 1$ and thermal coefficient $\tau_f = 0$.[5] We also assumed that the periodic structures designed on the top of the substrates were made from perfect electron conductor (PEC).

Purpose of this study is to calculate the frequency change of some metamaterials properties, i.e. the change of sign of internal constants and/or the existence of optical bandgaps, in the case of no periodicity (only one layer of periodic structure made by PEC) along the axis of incidence of EM wave (*z*-axis). We studied this change in two cases of polarization of the electric field and supposing vertical incidence of EM wave on the surface of the two previous mentioned periodic structures. The results of this study can be important to metamaterials applications as one layer of periodic structures, located on top of single substrates, can be more easily fabricated than multi-layered ones.

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0955-2219/$ – see front matter
doi:10.1016/j.jeurceramsoc.2005.09.084

2. Theoretical background

In this study, we made calculation of internal constants of metamaterials by using the Nicolson–Ross method.[6] According to this method, the relative complex internal constants ε (with $\varepsilon \equiv \varepsilon' + j\varepsilon''$) and μ (with $\mu \equiv \mu' + j\mu''$) for a slab material at frequency f can be calculated from its thickness d and the complex S^*-parameters at that frequency. Their values are given by the formulas:

$$\varepsilon = \sqrt{c_2/c_1} \text{ and } \mu = \sqrt{c_1 c_2} \tag{1}$$

where,

$$c_1 = \left(\frac{1+\Gamma}{1-\Gamma}\right)^2 \text{ and } c_2 = -\left(\frac{c}{2\pi f d}\ln(1/z)\right)^2 \tag{2}$$

$$z = \frac{V_1 - \Gamma}{1 - V_1\Gamma} \tag{3}$$

$$\Gamma = x \pm \sqrt{x^2 - 1} \tag{4}$$

with the sign selected in order to have $|\Gamma| \le 1$

$$x = \frac{1 - V_1 V_2}{V_1 - V_2} \tag{5}$$

and

$$V_1 = S^*_{21} + S^*_{11} \text{ and } V_2 = S^*_{21} - S^*_{21} \tag{6}$$

In our case, we supposed that internal constants are the effective constants of metamaterial and a FORTRAN software has been written for the calculation. The used complex S^*-parameters, which we need in our calculation, were found from EM simulations using FDTD method and appropriate software.

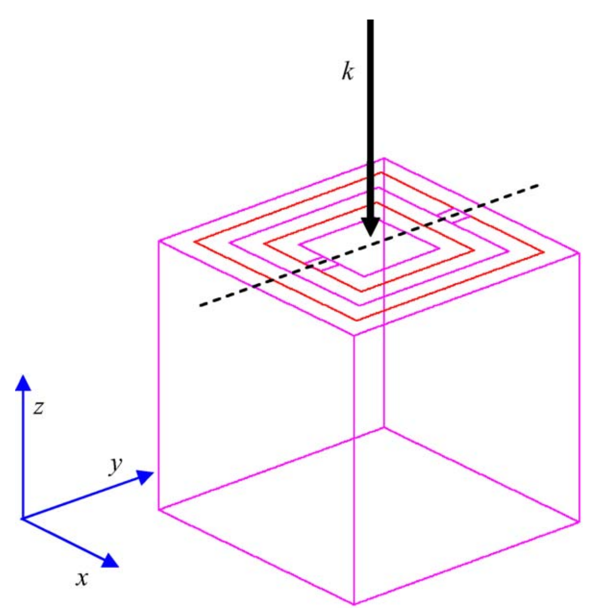

Fig. 1. Double slit tetragonal resonators with unit cell size 1.2 mm × 1.2 mm × 1.2 mm. The size of the tetragonal resonators is 1.0 mm × 1.0 mm for the outer and 0.6 mm × 0.6 mm for the inner one. The size of both tetragonal slits is 0.1 mm × 0.1 mm. Axis of slits is shown.

3. EM simulations results and discussion

In Fig. 1, we present the cubic unit cell of a metamaterial expanded in the xy-plane without periodicity in z-axis (one layer). In Figs. 2 and 3, we present the calculated S-parameters

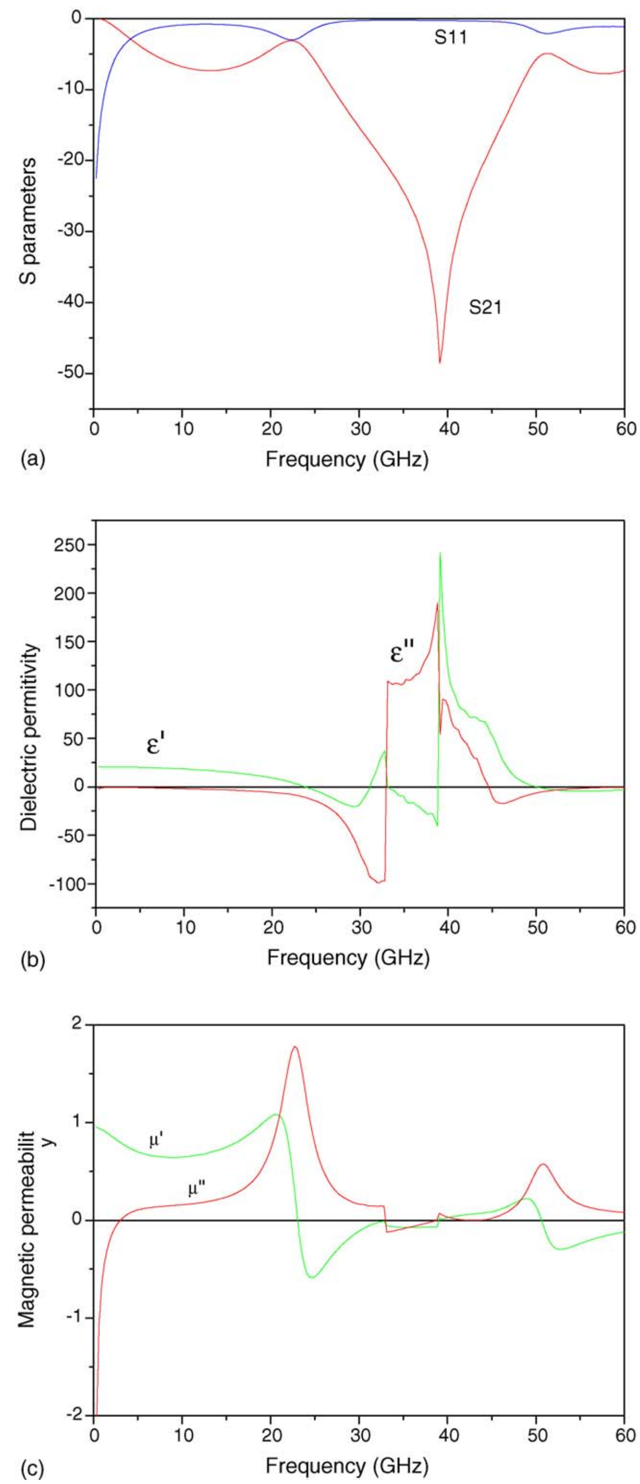

Fig. 2. Double slit tetragonal resonators: (a) calculation of S-parameters; (b) calculation of complex dielectric constants; and (c) calculation of complex magnetic constants. The electric field of the incident EM wave is parallel to the slits axis.

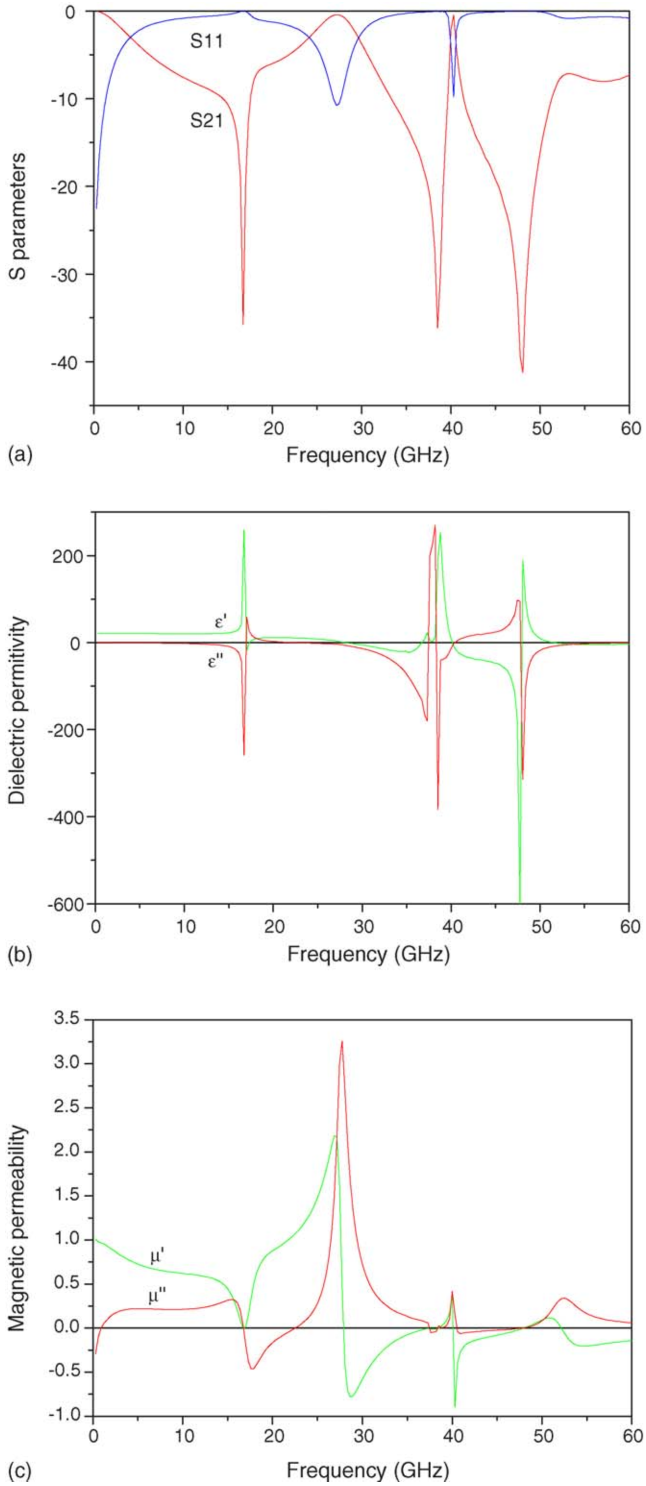

Fig. 3. Double slit tetragonal resonators: (a) calculation of *S*-parameters; (b) calculation of complex dielectric constants; and (c) calculation of complex magnetic constants. The electric field of the incident EM wave is vertical to the slits axis.

by FDTD method together with the corresponded calculated complex internal constants (dielectric permittivity and magnetic permeability) for this metamaterial, when the electric field of the vertically incident EM wave is parallel (Fig. 2) and vertical to the slits axis (Fig. 3).

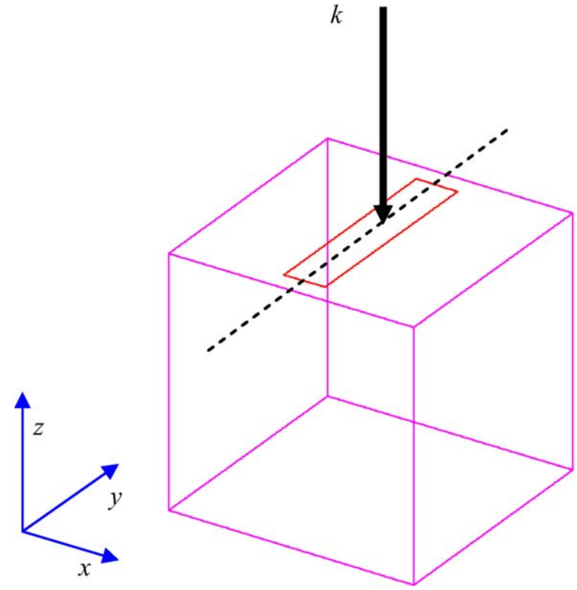

Fig. 4. Microstrip (wire) resonators with unit cell size 1.2 mm × 1.2 mm × 1.2 mm. The width of microstrip is 0.2 mm and the length 1.0 mm. Axis of microstrip is shown.

In Figs. 2 and 3, we observe that both real internal constants are equal to zero, at the frequencies where *S*-parameters show enough strong resonances. We also observe optical bandgaps (OBG) in the areas where $\varepsilon' > 0$ and $\mu' < 0$ or $\varepsilon' < 0$ and $\mu' > 0$, as in these cases there is no transmission of the incident EM wave through the metamaterials. These OBGs correspond to $S_{11} = 0$ (perfect reflection). The real internal constants are found to be equal to zero at the starting and ending frequency of bandgap. In Fig. 2, we observe positive real internal constants ($\varepsilon' > 0$, $\mu' > 0$) of the material from 0 to 23 GHz, negative real internal constants from 23 to 31 GHz, a small OBG area from 31 to 32.5 GHz, negative real internal constants from 32.5 to 38.5 GHz, positive real internal constants from 38.5 to 50 GHz and negative real internal constants from 50 to 60 GHz and so on. In this metamaterial, we observe existence of a complicated EM behavior relative to frequency change with more than one negative real internal constant. In Fig. 3, we observe a different EM behavior of the same metamaterial as we have a different polarization of electric field (vertical to the slits axis) of the incident EM wave. Again, we observe multiple frequency areas with negative real internal constants.

In Fig. 4, we present the cubic unit cell of another metamaterial with microstrip structure expanded in the *xy*-plane without *z*-axis periodicity. This microstrip periodic structure can be observed under the previously mentioned point of view and shows again a lot of interesting EM phenomena, for the case where the vertically incident EM wave has electric field with direction parallel (Fig. 5) and vertical (Fig. 6) to the microstrips axis. In both Figs. 5 and 6, we observe again transitions from positive to negative real internal constants at different frequency areas but not existence of any optical bandgaps. Possibly, this can be due to the selected geometric size of the microstrips.

One more interesting result of our analysis, in Figs. 2, 3, 5 and 6, is the observation of high positive values of internal

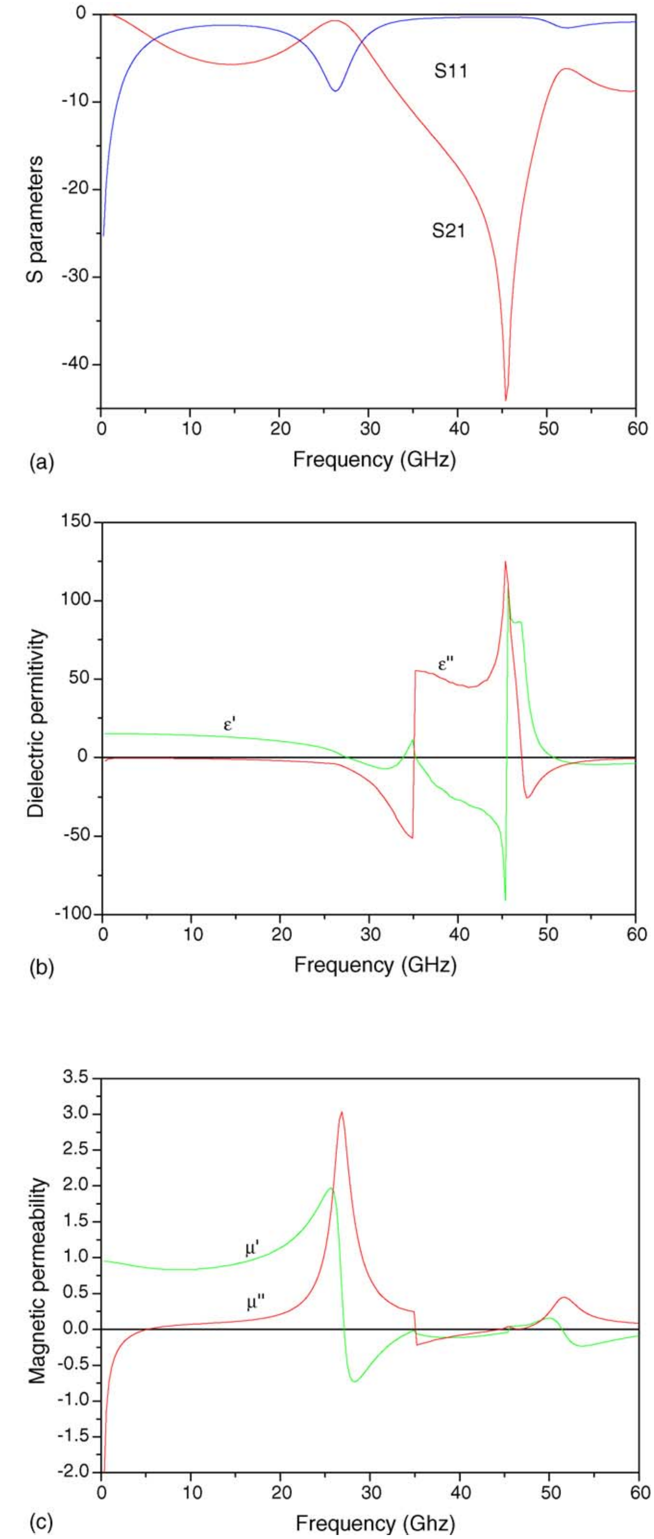

Fig. 5. Microstrips (wires) resonators: (a) calculation of *S*-parameters; (b) calculation of complex dielectric constants; and (c) calculation of complex magnetic constants. The electric field of the incident EM wave is parallel to the microstrips axis.

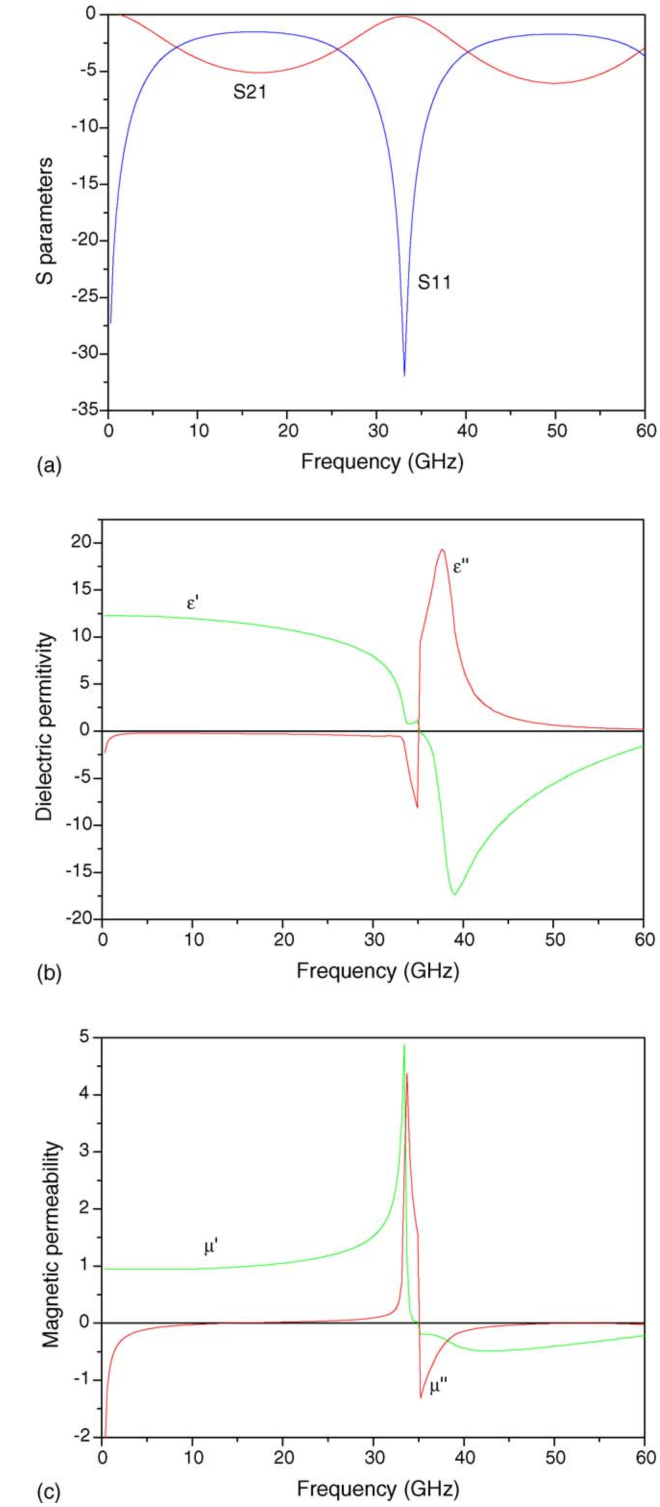

Fig. 6. Microstrips (wires) resonators: (a) calculation of *S*-parameters; (b) calculation of complex dielectric constants; and (c) calculation of complex magnetic constants. The electric field of the incident EM wave is vertical to the microstrips axis.

constants close to some of the zeros of real constants or close to DC field (i.e. in Fig. 2b, $\varepsilon' \approx 22$). These values are sometimes much higher than the corresponding constants of the used material for substrate, in our case of forsterite ($\varepsilon' = 11$ and $\mu' = 1$). Finally, the presence of very small positive values of one or both real internal constants (<1) can give ultra low index (ULI) optical phenomena at specific frequency areas with enough high S_{21} values (i.e. Fig. 3b, for ε' and $f \sim 27$ GHz or in Fig. 6c for μ' and

$f \sim 33$ GHz). The designs presented here were not optimized to improve further this behavior.

4. Conclusion

In this study, we predict the EM behavior of two periodic structures in a relatively broad frequency area. We found existence of negative real internal constants at multiple frequency areas. We also predict for the used geometry of resonators the existence of optical bandgaps. We found that, the number of layers in z-axis (in our cases equals to 1) does not minimize the possibility to find negative real internal constants. The increase of real effective dielectric constants at values higher than the values of the dielectric substrate and the existence of ULI behavior, in some cases, is very promising for many future applications of metamaterials in communications and new devices. Finally, we found that the traditional metamaterials geometries of SRR and microstrips can be found even with opposite correspondence (SRR can have negative dielectric permittivity and microstrips negative magnetic permeability).

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