Metamaterial optical filter with maximal absorption coefficient

D Ionescu and G Apreotesei
Gh. Asachi Technical University of Iasi, Romania, Department of Telecommunications and Informational Technologies, Carol I Blvd. 11, 700506 Iasi, Romania, 2 Department of Physics, Dimitrie Mangeron Blvd. 67, 700050, Iasi, Romania
E-mail: danaity@yahoo.com

Abstract. Tunable transmission and absorption coefficients in visible and infrared range have been obtained for metamaterial filters with a structure of metal on dielectric nanocomponents. Materials were stacks of nanoconstituents placed in alternate layers, which present a maximum or a minimum of the transmission coefficient and convenient values of the absorption coefficient when the periodicity is interrupted in a controlled manner. A simulative set-up with the metamaterial sample in a channel waveguide was conceived for obtaining the S parameters at the field propagation, using the HFSS program. The plasmon dispersion at the metal / dielectric interface was taken into account for calculating the frequency dependent surface plasmon wave vector, which can be adjusted by modifying the refractive index and the electric permittivities of the constituents. Transmission coefficients have been calculated for different structure geometries. The optimal metamaterial configurations have been chosen, in function of the desired filtering effect, for a range of incident field wavelength of 600 – 900 nm. A transmission variation of about 50 … 80 % at the central frequency, in comparison with the transmission effects in the side bands has been demonstrated for the proposed metamaterial filters.

1. Introduction
For obtaining filtering effects in visible and infrared range are necessary structures with nanometric components. Metamaterials are perfect candidates, offering tunable properties by modifying the structure geometry and constitutents nature [1, 2].

Our task is to synthesize a metamaterial filter structure by modifying the design for obtaining tunable absorption and transmission coefficients in a desired frequency range. We have proposed a geometrical structure of metal on dielectric nanocomponents, analyzed by simulation techniques using the HFSS program.

2. Metamaterial structure for filtering

2.1. Samples design
The proposed metamaterial filter structure consists of a stack of 2 – 4 layers including repetitive unit cells which implement a specific transfer function of the filter type. We have considered here a range of incident field wavelength of 600 – 900 nm (about 300 – 500 THz).
In this case, the unit cell dimensions are of tens to hundreds of nanometers and include metal on dielectric nanoconstituents.

The role of multiple layers is to offer the possibility of interrupting the periodicity of the neighbour unit cells by subtracting some unit cells in a controlled manner. This structure generates an anomaly of some physical parameters. This anomaly can be a maximum or a minimum and we have speculated the extreme of the transmission coefficient of the unit cells and convenient values of the absorption coefficients of the stack of layers.

We have considered unit cell dimensions of about $\frac{1}{4}$ of minimum wavelength: 120 - 180 nm. The periodicity interruptions were at dimensions of 10 to 20 % higher than maximum wavelength of the applied external field: at 1000 nm (1 μm) in our case, on both axes in plane. In the corresponding positions in the layer, the unit cells have been extracted. The result is to increase the absorption effect in the metamaterial. Global dimensions of the metamaterial filter attached to the visible range waveguides and transmission lines were of a few micrometers order.

The 3D structure of the metamaterials was reproduced with the HFSS program. Metallic segments were included in a dielectric substrate, in order to obtain distributed capacitances, inductances, respectively resistances, necessary for a specified filter effect. The unit cell structure depends on the filter type. In the figures 1 and 2 we have illustrated the unit cell geometry and the equivalent scheme for a narrow band filter, respectively a stop band filter.

The metallic segments dimensions were: length, $l$, of about 20 nm; width, $b$, of about $l / 10$ (2 nm) and width of the resistive paths, $t$, of about $l / 20$ (1 nm), adjustable by simulations until the desired transfer function has been obtained. Spacing between the unit cells in plane was comparable with $l$ dimension.

Different central frequencies of the filters have been tested, corresponding to different values of the circuit elements, respectively to different dimensions of the geometrical elements inside the unit cell. We have illustrated here the design strategy for the metamaterial filter having a central frequency $f_0 = 410.9$ THz. ($L = 0.05$ pH, $C = 0.003$ fF)

The narrow band filter has the unit cell given in figure 1(a). Metallic segments (represented in the picture) were inserted in the dielectric substrate. Its equivalent circuit in presented in figure 1(b) and the simulation results in Orcad in figure 1(c).

![Figure 1. Metamaterial model for a narrow band filter with central frequency of 410.9 THz. a) geometry of the unit cell; b) equivalent circuit of the unit cell; c) transfer function; d) layer region.](image)

The unit cell proposed by us replaces the following classic structure given in literature [2, 3], having the same frequency behaviour in the considered domain of about 300 – 500 THz:
Our structure removes the disadvantage of impedance loops which can be perturbed by the external fields.

The stop band filter based on metamaterial structure has the unit cell given in figure 3. The filtering effect is very selective and the valley magnitude is amplified by multiplication of the unit cell in the metamaterial layers. The same strategy of controlled removing of the unit cells in the layers has been applied. Notations for the dimensions of the metallic segments have been illustrated on the picture.

2.2. Testing configuration
The metamaterial structure of the filters imposes a specific analysis of the field propagating through the sample. We have considered a metal / dielectric combination of materials, with metallic segments included in a dielectric substrate. Configuration of the segments generates capacitances, inductances and electrical resistances distributed on the length, which can be adjusted by modifying the dimensions. The proper combination of the circuit elements has to be set in each case, in order to obtain a specific equivalent scheme, which will have the desired transfer function, with a peak, respectively valley as sharp as possible.

The plasmon dispersion at the metal / dielectric interface was taken into account for calculating the frequency dependent surface plasmon wave vector, which can be adjusted by modifying the refractive index and the electric permittivities of the constituents. For a silver on Si$_3$N$_4$ combination (Au and Ag have the real part of the permittivity negative within a certain frequency range of UV to NIR) we have:

\[
k_{sp} = \frac{2\pi}{\lambda} n_{del} \sqrt{\frac{\varepsilon_{metal}}{\varepsilon_{metal} + \varepsilon_{del}}}
\]  

(1)
Where $k_{sp}$ is the surface plasmon wave vector, $n_{diele}$ is the refractive index of the dielectric and $\varepsilon_{metal}$, respectively $\varepsilon_{diele}$ are the electric permittivity of the metal, respectively dielectric [4, 5].

We have considered for the metamaterial analysis a simulational set-up with the metamaterial sample in a multi-mode ridge channel waveguide ($d = 4.6 \mu m$, $g = 2.5 \mu m$) (figure 4). The $S$ parameters have been calculated at the field propagation through the sample. The propagation mode was TE$_{10}$. With help of the HFSS program, the samples analysis was performed in the domain of 600 … 900 nm for the incident field wavelength.

![Figure 4. Simulational set-up for determining the metamaterial physical parameters.](image)

The normalized frequency (V number, which determines the number of modes) of this rectangular waveguide can be written as [2, 6]:

$$V = \frac{2\pi}{\lambda} d \sqrt{n_{meta}^2 - n_{cladding}^2}$$

(2)

where $n_{meta}$ and $n_{cladding}$ are the refraction index of the metamaterial slab, respectively substrate and $d$ is the metamaterial slab width. For the TE mode, $E_z = 0$, $E_x \gg E_y$, and $H_z \neq 0$. The considered channel waveguide is a nonplanar one and has strong optical confinement because it is surrounded on three sides by air, which is a low-index material ($n_{cladding} = n_{air} \approx 1$). The waveguide substrate is of SiO$_2$.

Transmission and absorption coefficients have been calculated with the following relations [2, 7]:

$$T = |S_{21}|^2 ; \quad A = 1 - |S_{11}|^2 - |S_{21}|^2$$

(3)

using the $S$ parameters determined by simulation.

3. Results for filter parameters

For the two types of synthesized filters, narrow band, respectively stop band filter, the transfer function corresponding to the 3D metamaterials structure has to be determined. The transfer function evolution is described in our case by the transmission and absorption coefficients of the structures.

These coefficients have been calculated and represented on parametrical graphs, in function of the structure geometry. The optimal geometrical parameters and metamaterial sample configuration have been chosen, in function of the desired results in a frequency range corresponding to incident field wavelength of 600 – 900 nm.

The central frequency of the filter can be tuned by modifying the geometrical dimensions of the metal segments in the metamaterial structure and their spacing. The considered metal / dielectric materials combination was Ag on Si$_3$N$_4$. Other combinations reported in literature can be used [2, 4], like Ag or Au on SiO$_2$, Si$_3$N$_4$, Ag, Al on quartz, Al on polymer, etc. The same analysis method for structure optimization can be applied.
The transmission coefficient for the two types of considered filters, narrow band, respectively stop band filter, calculated on the basis of the simulation data are indicated in figure 5. Simulations have been developed for a unit cell.

![Graph](image1)

**Figure 5.** Transmission coefficient for the narrow band filter (a), respectively stop band filter (b), with central frequency of 410.9 THz. Results calculated using the simulation data.

Results obtained using the 3D structural simulation are in good agreement with the results obtained for the transfer function in Orcad (see figures 1 and 3).

We are dealing with a tunable structure, for which the central frequency of the filter can be changed by modifying the dimensions of the metallic segments in the unit cell and their spacing. The same set of results, by 3D simulation and simulation of the equivalent circuit can be performed in the same manner for each central frequency is set.

For optimizing the metamaterial structure dimensions for a given central frequency of the filters, some parametric curves have been obtained by structural simulation. In figure 6 is indicated the evolution of the transmission coefficient in function of the electric permittivity of the dielectric substrate of the metamaterial, for filters having different values of the central frequency, in the considered range.

![Graph](image2)

**Figure 6.** Transmission of the metamaterial sample in function of: (a) the electric permittivity of the dielectric inside, $\varepsilon_{\text{rel}}$ and (b) the filling factor with metal in the structure.
A maximum can be observed on each curve, indicating the optimal value for the dielectric substrate relative permittivity. In our case, we have analyzed a filter with the central frequency of 410.9 THz using a Si$_3$N$_4$ dielectric substrate having $\varepsilon_{r_{\text{dieu}}}$ = 10. According to the graphs (see the red curve), the optimal value for $\varepsilon_{r_{\text{dieu}}}$ is about 5, but for an $\varepsilon_{r_{\text{dieu}}}$ of 10, high enough transmission coefficient can be obtained (between 0.7 and 0.8).

One observes that low permittivities substrates are recommended for synthesizing the metal/dielectric filters ($\varepsilon_{r_{\text{dieu}}} < 5 \ldots 10$, depending on $f_0$).

The graphs in figure 6(b) indicate that the transmission decreases when the metal content in the metamaterial layers increases. A filling content of about 0.2 was considered for exemplification in our study, ensuring a transmission coefficient high enough. Consequently the recommendation for metamaterial synthesizing is to dispose the metallic segments not very dense in the layer. In the same time, a dense disposal of metallic segments can generate parasitic unwanted coupling between elements, which has to be avoided.

4. Conclusions
Transmission coefficients and transfer function have been determined for metamaterial filters having metal segments included in a dielectric substrate. Segments disposal was set in order to obtain convenient impedances (capacitive, inductive, respective resistive) in the unit cell, corresponding to a certain type of filter.

Very selective narrow band, respectively stop band filters were set, in the frequency domain of about 300 – 500 THz (600 – 900 nm). Filter performances depends on structure geometry. The optimal geometrical parameters and metamaterial sample configuration have been chosen, in function of the desired results in a frequency range. A transmission variation of about 50 … 80 % at the central frequency, in comparison with the transmission effects in the side bands has been demonstrated for the structure. The method offers the possibility of a new structure design, having the physical parameters in a convenient range.

5. References
[1] Sun D, Qi L, Liu Z 2020 Results in Physics 16 102887.
[2] Yun S 2011 Novel Optical Metamaterials, Absorbers, and Filters Based on Periodic Nanostructures, Dissertation, College of Engineering, The Pennsylvania State University.
[3] Yue L, Ji S, Yan B, Tung N T, Lam V D, Wang Z 2016 Progress in Electromagnetic Research Symposium (PIERS), Shanghai 2303-2303.
[4] Toudert J, Camelio S, Babonneau D 2005 Reviews on Advanced Materials Science 10(2) 123-127.
[5] Pacheco-Peña V, Engheta N 2020 Nanophotonics 9(2) 379–391.
[6] Jia X Q, Chen Q, An Q, Zheng Y J, Fu Y Q 2020 AIP Advances 10, 055018.
[7] Zhu Z, Zhang X, Gu J, Singh R, Tian Z, Han J, Zhang W 2013 IEEE Transactions on Terahertz Science and Technology 3(6) 832-837.