ON INCREASING THE EFFICIENCY OF FREQUENCY CONVERSION IN METAMATERIALS

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In this article calculation of the optimal length of a metamaterial for effective transformation of frequency on the given length in similar environments is considered.

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As for back as 1967 the Soviet physicist Victor Veselago showed that media with negative indices of magnetic permeability μ and dielectric permittivity ε at the same time, media called metamaterials, must possess the negative index of refraction. The values of these indices, in their turn, depend on wave length of electromagnetic radiation passing through the medium [1]. The achievements in experimental elaboration of metamaterials aroused new interest for theoretical and experimental researches of optical nonlinear properties of similar artificially created media with unique electromagnetic properties [2–8].

In recent years there have been carried out studies on elaboration of metamaterials refracting visible light. Generation of optical harmonics in metamaterials was considered in a series of works, mainly, in constant–field approximation [4, 6–8]. In contrast to constant-field approximation, constant-intensity approximation of fundamental radiation [9–10] does not impose any restrictions for phase of interacting waves. It permits to make more strict analysis of nonlinear interaction of waves in material with regard for change of interacting waves phases. In constant-intensity approximation it is possible to depict physical peculiarities of nonlinear process [11–12], which are unamenable to study within the frames of widely applied constant-field approximation. The investigations in this direction go on.

As a consequence, in the present work the results of further study are reported. Just namely analysis of the ways of increasing the efficiency of radiation energy conversion into second harmonic in metamaterials. It is particularly shown that maximum of the efficiency of conversion to second harmonic depends directly on a full length l of investigated metamatirial.

The process of generation of second harmonic in metamaterial is described by the system of reduced equations of kind [4]

$$\frac{dA_1}{dz} + \delta_1 A_1 = i\frac{8\pi\varepsilon_1\omega_1^2}{k_1c^2}\chi_{eff}^{(2)}A_1^*A_2\exp(i\Delta z),$$
$$\frac{dA_2}{dz} + \delta_2 A_2 = i\frac{4\pi\varepsilon_2\omega_2^2}{k_2c^2}\chi_{eff}^{(2)}A_1^2\exp(-i\Delta z), \quad (1)$$

where $A_{1,2}$ are complex amplitudes of pump wave and second harmonic at frequencies $\omega_{1,2}$ respectively, $\delta_{1,2}$ are the coefficients of wave absorption in metamaterial at frequencies $\omega_{1,2}$ respectively, $\varepsilon_{1,2}$, $\mu_{1,2}$ are dielectric permittivity and magnetic permeability of metamaterial at corresponding frequencies, $\Delta = k_2 - 2k_1$ is the phase mismatch between interacting waves, $k_{1,2}$ ($k_{1,2} > 0$) are moduluses of wave vectors $\vec{k}_{1,2}$ directed towards the opposite to axis z, $\chi_{eff}^{(2)}$ is the efficient quadratic susceptibility of material [13].

We carry out study in following boundary conditions

$$A_1(z=0) = A_{10}\exp(i\varphi_{10}), \quad A_2(z=l) = 0. \quad (2)$$

There $z = 0$ corresponds to an entrance to metamaterial, φ_{10} is an initial phase of pump wave at the entrance to nonlinear medium.

By solving the system of reduced equations in constant-intensity approximation of fundamental radiation with regard for (2), for complex amplitude of harmonic wave at length z of nonlinear medium there was received ($\delta_{1,2} = 0$) [10]

$$A_2(z) = \frac{i\gamma_2 A_{10}^2}{\lambda' + \frac{i\Delta}{2}\operatorname{tg}\lambda' l}(\sin\lambda' z - \operatorname{tg}\lambda' l\cos\lambda' z)\times$$
$$\times\exp(i2\varphi_{10} - i\Delta z/2) \quad (3)$$

where

$$\lambda'^2 = \frac{\Delta^2}{4} - 2\Gamma^2, \quad \Gamma^2 = \gamma_1\gamma_2 I_{10}, \quad I_j = A_j A_j^*.$$

For the efficiency of conversion of pump wave energy to energy of harmonic wave (or given intensity of second harmonic wave) in metamaterial (3) we receive

$$\eta_2(z) = \tilde{I}_2 = \frac{I_2(z)}{I_{10}} = \gamma_2^2 I_{10}\frac{(\sinh\lambda z - \tanh\lambda l\cosh\lambda z)^2}{2\Gamma^2 + \frac{\Delta^2}{4}(\tanh^2\lambda l - 1)} \quad (4)$$

at

$$\Gamma^2 > \frac{\Delta^2}{8}, \text{ где } \lambda^2 = 2\Gamma^2 - \frac{\Delta^2}{4}.$$

As is known, behavior of dependence of conversion efficiency sharply differs from usual dependence of conversion efficiency $\eta_2(z)$ in natural material. If in general quadratic nonlinear medium there took place strongly pronounced maximum reached on coherent length of medium, then in considered case of medium with negative refraction there is observed monotonous behavior of dependence. With this, metamaterial plays the role of a mirror reflecting harmonic wave on entry of metamaterial, i.e. maximum of conversion falls not on outlet, but an entry of metamaterial. In other words, excited radiation of harmonic is directed to meet exciting pump wave.

The numerical analysis of the analytical expression of maximum efficiency of conversion $\eta_{2,max}(z)$ in metamaterial, received with regard for phase changes of interacting waves depending on full given length Γl of metamaterial is offered in Figure.

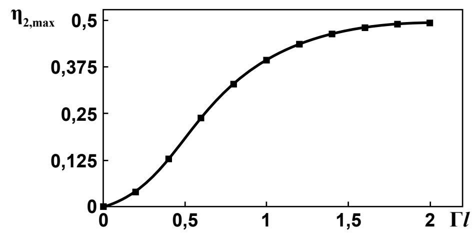

Fig. Dependence of maximum efficiency of conversion $\eta_{2,max}(z)$ on the given full length of metamaterial Γl at $\Delta z/2 = 0{,}08$, $\delta_{1,2} = 0$

In figure it is seen that maximum value of the efficiency acquires the constant value, i.e. in dependence the regime of saturation is observed. Hence practically an important conclusion follows. In constant-intensity approximation it is possible to calculate the optimum value of full length l of metamaterial for the purpose of obtaining the efficient frequency conversion on this length of similar media.

References:

1. V.G. Veselago. Usp. Fizich. Nauk, 92 (1967) 517-526.
2. Marqués Ricardo; Kivshar Yuri. Appl. Phys. Lett. 95, (2009) 084105-084109.
3. Fu Xiang Wang, F.J. Rodriguez, Hannu Husu, M. Kauranen, Nonlinear Optics and Quantum Optics, 40 (2010) 43-56.
4. A.K. Popov, and V.M. Shalaev, Appl. Phys. B 84 (2006) 131-137.
5. S.M. Orbons, D. Freeman, B. Luther-Davies, B.C. Gibson, S.T. Huntington, D.N. Jamieson, A. Roberts. Physica B, 394 (2007) 176-179.
6. I.R. Gabitov, B. Kennedy, A.I. Maimistov, IEEE J. Select. Top. Quantum Electron., 16 (2) (2010) 401-409.
7. V.M. Agranovich, Y.R. Shen, R.H. Baughman, and Zakhidov, Phys. Rev. B 69 (2004) 165112-165119.
8. I.V. Shadrivov, A.A. Zharov, and Yu.S. Kivshar, JOSA B 23(2006) 529-534.
9. Z.H. Tagiev, A.S. Chirkin, Zh.Eksper. Teor. Fiz. [Sov. Phys. JETP] 73 (1977) 1271-1282.
10. Z.H. Tagiev, R.J. Kasumova, R.A. Salmanova, and N.V. Kerimova, J. Opt. B: Quantum Semiclas. Opt., 3, (2001) 84-87.
11. Z.H. Tagiev, R.J. Kasumova, L.S. Gadjieva, Journal of Russian Laser Research, 32 (2011) 188-199.
12. R.J. Kasumova, L.S. Gadjieva, Proc. IV International Scientific – Practical Conference, Kiev-Colambia, 4 (2011) 216-217.
13. F. Zernike, and J.E. Midwinter, Applied Nonlinear Optics, New-York: Willey, 261p (1973).