JOURNAL OF APPLIED PHYSICS **102**, 043101 (2007)

Negative refractivity assisted optical power limiting

Alexander Baev, Edward P. Furlani, Marek Samoc, and Paras N. Prasad[a)]
The Institute for Lasers, Photonics and Biophotonics, State University of New York at Buffalo, Buffalo, New York 14260

(Received 1 May 2007; accepted 27 June 2007; published online 16 August 2007)

We propose an approach for achieving optical power limiting (OPL) using planar multilayered media. The approach involves the use of multiple bilayer structures that consist of a negative index (NIM) layer followed by a nonlinear two-photon absorbing (TPA) layer. The NIM layers refocus light in the TPA layers to increase intensity and nonlinear absorption. We perform parametric two-dimensional finite difference time domain simulations and compute the power transmittance of the media as a function of the incident light intensity, the number of layers, the layer thickness, and the material properties. Our analysis demonstrates proof-of-concept and indicates that the TPA-based OPL can be enhanced and optimized using NIM focusing. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2769144]

I. INTRODUCTION

There is substantial research activity for the development of perspective concepts in optical power limiting (OPL) which is stimulated by commercial and military applications involving protection of the human eye against accidental or deliberate exposure to laser radiation.[1] Two-photon absorption (TPA) materials are of particular interest for such applications because of their instantaneous response and high linear transmittance at low optical power.[2–9] However, typically achievable two-photon absorption coefficients (e.g., in the range 1–100 cm/GW) do not provide sufficiently low clamping fluence for two-photon absorbers to be used without focusing.

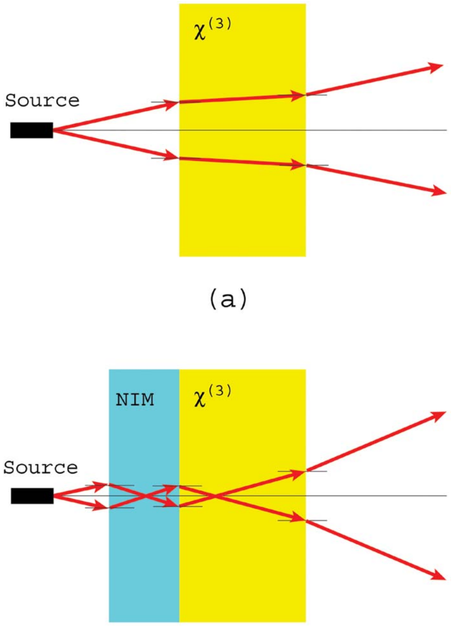
In this article we propose a mechanism for the enhancement of TPA-based OPL that utilizes light focusing by negative index materials (NIMs). The unusual properties of NIMs, such as capability of imaging beyond the diffraction limit,[10–12] have caused tremendous interest in such materials that has led to a number of theoretical achievements[13–16] and to the experimental realization of NIMs at optical frequencies.[17–19] While substantial research continues into the development of NIMs, there have been relatively few studies of nonlinear optical effects in the presence of negative refractivity and their possible applications. In particular, the combination of the possibility of focusing of light by a NIM slab with intensity dependent effects such as nonlinear absorption deserves studies. We consider here a simple case of an optical structure with combined nonlinear and NIM behavior. Specifically, we study planar TPA-based OPL media consisting of interleaved NIM and TPA layers. Each NIM layer focuses or refocuses light into its associated TPA layer, thereby increasing local intensity and therefore absorption in the TPA layer. We perform parametric two-dimensional (2D) finite difference time domain (FDTD) simulations to determine the OPL efficiency of the media. We compute the transmittance of the media as a function of the number of layers, the layer thickness, and the material properties. Our analysis demonstrates that TPA-based OPL can be enhanced and optimized using NIM focusing.

II. MODEL

In a conventional OPL system an intense laser pulse is incident on a material—often a solution of an organic dye—with a high nonlinear absorption coefficient [Fig. 1(a)]. For a pulse with intensity $I(t,z)$ the attenuation in the TPA layer is described by the following equation:

$$\left(\frac{\partial}{\partial z}+\frac{1}{c}\frac{\partial}{\partial t}\right)I(t,z)=-\alpha I(t,z)-\beta I^2(t,z), \tag{1}$$

where α is linear absorption coefficient and β is the two-photon absorption coefficient. In our simulations we assume



(b)

FIG. 1. (Color online) One-layered NIM assisted OPL.

[a)] Electronic mail: pnprasad@buffalo.edu that the nonlinear material is completely transparent for weak radiation ($\alpha=0$). Figure 1 shows the principle of operation of a structure containing a NIM layer and a TPA layer compared to a TPA layer alone. For simplicity, the source of radiation is placed in front of the both structures. In conventional OPL systems, light is focused by a lens (imaging system, typically $f/5$) with the focal plane inside the TPA medium. The particular geometry of media considered here can be thought of as an element of an OPL system placed immediately after focus, so light is refocused by the NIM layers, which precede each TPA layer [Figs. 1(b) and 3(b)].

III. RESULTS AND DISCUSSION

A. 2D FDTD simulations of a bilayer system

We first study a single NIM-TPA bilayer structure in air. The thicknesses of the NIM and TPA layers are 3 and 16 μm, respectively. The wavelength of the incident radiation is 800 nm. The linear refractive index of the TP material is set to 1.4. The refractive index of the NIM is -2 (Refs. 19 and 20) and we assume that this material is transparent at 800 nm. These parameters are chosen to provide a first glimpse of the problem only; more realistic simulations would need to address the problem of the possibility of achieving highly negative values of the refractive index in the presence of linear absorption losses which are unavoidable in the vicinity of material resonances. The imaginary part of the third order nonlinear susceptibility of the TP material is taken to be $\Im m\{\chi^{(3)}\}=10^{-20}\ \mathrm{m}^2/\mathrm{V}^2$, which, at the wavelength of 800 nm, corresponds to the two-photon absorption coefficient $\beta \approx 5$ cm/GW or, at a dye concentration of 0.02 M, to the two-photon absorption cross section of $10^{-46}\ \mathrm{cm}^4$ s (10 000 Goeppert–Mayer units).[21]

The choice of the layer thicknesses deserves a special comment: The thicknesses of the layers were chosen to (i) ensure nonlinear transmittance at the level of 10%–30% (at a given incident power) as in the typical optical limiting experiments and (ii) dispense with excessive computational resources as serial FDTD simulations in the optical range are computationally demanding. The system is illuminated by a TE polarized Gaussian continuous wave (cw) source positioned behind the NIM layer in air (Figs. 1 and 3). The maximum instantaneous power of the source is 1 kW. For a rather thin medium which we are modeling here this can be taken to represent a real life nanosecond source with microjoule range pulse energy. The distance between the source and the closest medium boundary is 1 μm; the beam waist radius is 5 μm, which implies rather tight focusing. We did not analyze performance of our model system at different distances from the source, although various degree of divergence of the beam, occurring in a real experiment, can be easily simulated by changing the beam waist radius. We analyze the performance of the structure using 2D FDTD analysis, which was implemented using the RSoft Fullwave software.[22] All boundaries in the simulation are assumed to be perfectly matched layers.

We compute the transmitted power (behind the TPA layer) without and with the NIM layer present (Fig. 2). We find that when the NIM layer is present [Fig. 2(b)], the steady-state time-averaged output power, which is normalized to the source power (i.e., the transmittance), is 0.15. This is in contrast to the case without the NIM layer [Fig. 2(a)], which yields the transmittance of 0.25.

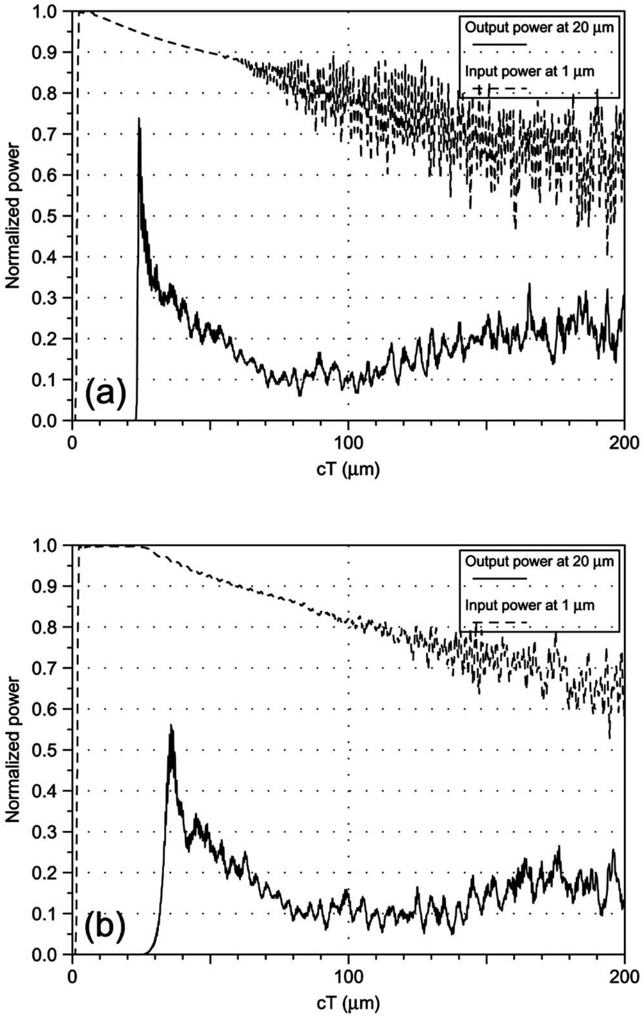


FIG. 2. (a) Output power after passing through a 16 μm layer of TP material. (b) Output power after passing through a 3 μm layer of NIM material followed by a 16 μm layer of TP material. Here, c is the speed of light in free space and T is the running time.

Note that in these simulations there is an initial transient peak in the computed transmitted power, which is due to fact that the input signal is ramped up over a finite time span. Also, the input power should not be confused with the source power—it is the value of the power at the entrance to the medium. The input power decreases and oscillates with time because of multiple reflections on the interfaces. By comparing Figs. 2(a) and 2(b), we find that the NIM layer introduces a delay in the output radiation, which could potentially be used for slow light applications (optical delay lines). We compute the transmitted power after it has plateaued and we time-average the computed values to account for numerical noise.

B. FDTD simulations of 2D multilayered media

We have also studied multilayered media consisting of multiple NIM-TPA bilayers (of the same material properties

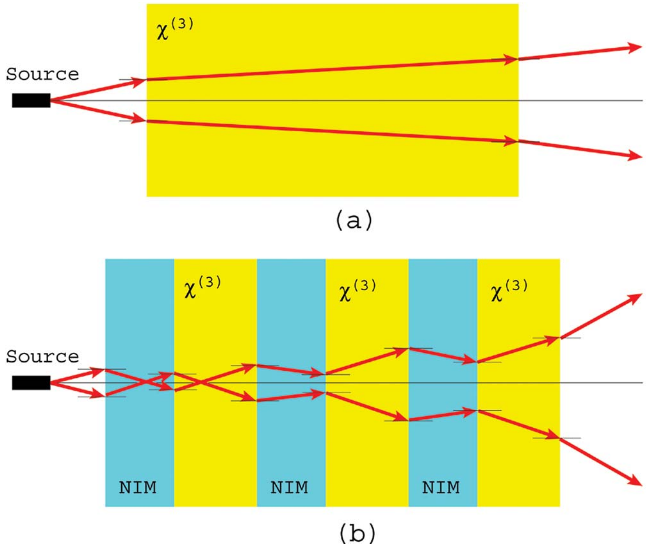


FIG. 3. (Color online) Multilayered NIM assisted TPA.

as those in the first example shown in Fig. 1) as shown in Fig. 3. To calibrate our analysis we first determine the propagation through a single 12.5 μm reference TPA layer [Fig. 4(a)]. Next we analyze a sequence of multilayered media consisting of N identical bilayer structures each having a 2.5 μm NIM layer followed by a 2.5 μm TPA layer. We first set $N=5$, which makes the total thickness of the media equal to 25 μm, i.e., $5\times(2.5$ μm NIM layer$+2.5$ μm TPA layer). As the total thicknesses of the TPA layers, with and without NIM layers, are equal in these simulations, the nonlinear absorption would be equally intense if the NIM layers did not focus the incident light, as each NIM layer is transparent by assumption. However, we find that the steady state transmittance of the reference TPA layer [Fig. 4(a)] is approximately three times that of the five bilayer media [Fig. 4(b)]. Note that the oscillations of the input power on the boundary between air and NIM layer are numerically proven to be independent of the grid. Apparently, these oscillations are physical and due to interference effects on the boundary between air (positive index material) and NIM. It is worthwhile to note that, while the number of NIM layers in the "sandwiched" structure does not change, the effectiveness of the power limiting decreases linearly as the total length of the TPA material decreases. As sketched in Fig. 3 this is likely due to the fact that the thickness of the consecutive NIM layers is not optimized for effective focusing into the TPA layers.

Next we study TPA enhancement as a function of the number of bilayers N. Specifically, we consider a sequence of N bilayered structures, but fix the total thickness of the TPA material in the media to 12.5 μm (i.e., the sum of the thicknesses of all of the TPA layers is fixed). We compute the transmittance for $N=1$, 2, 5, 7, and 10. Figure 5 shows the TPA enhancement factor, which is the ratio of transmittance without NIM layers to that with NIM layers, as a function of N. The analysis indicates a maximum enhancement factor of 2.6 for $N=6$. Thus, simply increasing the number of NIM layers does not result in larger TPA enhancement factors as one might guess. Having optimized the number of bilayers we computed OPL performance for $N=5$. The results are presented in Fig. 6. As one can see, the OPL curve of the bilayer structure shows the clamping level of $\sim$250 W, whereas for the reference medium the clamping level of

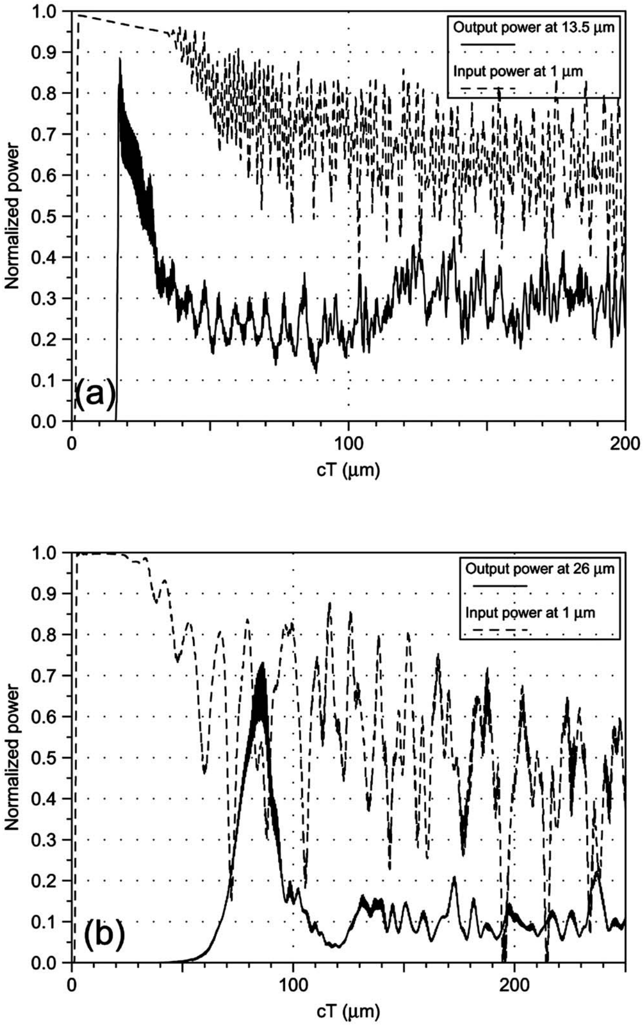


FIG. 4. (a) Output power after a single TPA layer l (12.5 μm, cw excitation). (b) Output power after propagation through five NIM/TPA bilayers.

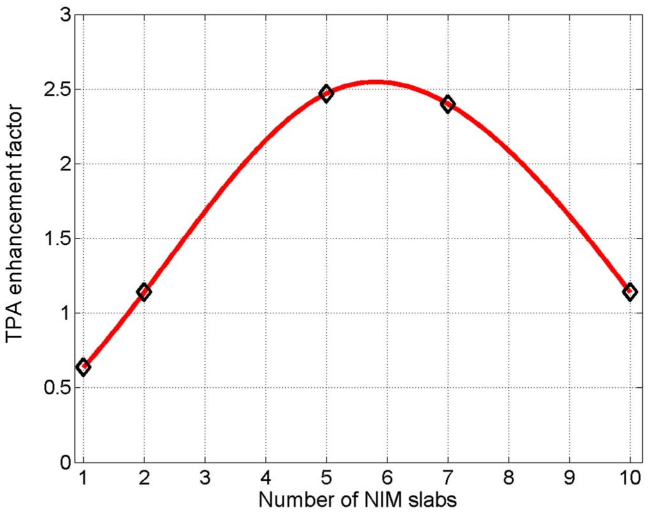


FIG. 5. (Color online) TPA enhancement factor for a sandwiched structure containing 12.5 μm of TPA material.

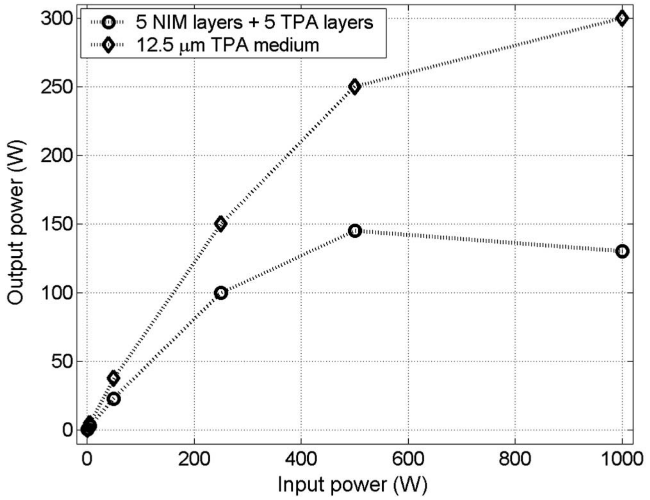


FIG. 6. Optical limiting curves of the reference TPA medium and a bilayer system with $N=5$.

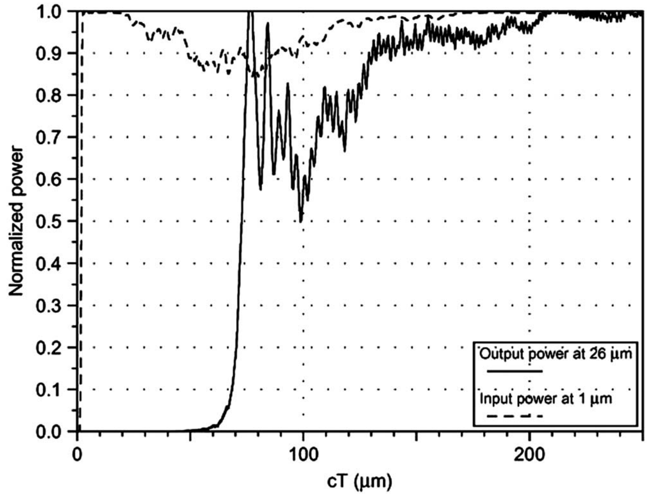


FIG. 8. Output power after propagation through the "sandwich" structure with total length of 25 μm (five NIM layers of 2.5 μm and five linear transparent layers of 2.5 μm).

~500 W is observed. The spatial distribution of the electric field for $N=5$ shown in Fig. 7(b) clearly indicates NIM focusing inside TPA layer.

We also performed a simulation of a composite material consisting of five NIM layers and five transparent linear layers with the same linear refractive index of 1.4 as that of the TP medium, to check whether the enhancement of TPA is only due to additional focusing and not due to some layered structure effects (Fig. 8). We find that in the absence of the two-photon absorbing medium the averaged steady-state output power equals the source power.

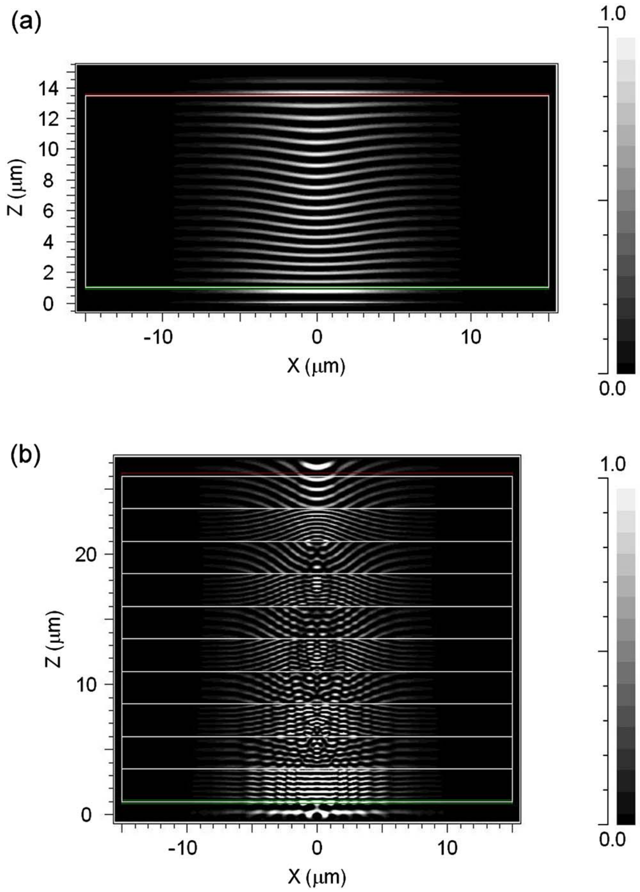


FIG. 7. (Color online) (a) Electric field distribution inside 12.5 μm TP layer. (b) Electric field distribution inside a five bilayer system.

Finally, we study the influence of the NIM layer thickness on the enhancement of two-photon absorption. We performed a simulation where the number of NIM layers is 2, but the thickness of each layer is 6.25 μm. The total length of NIM medium is then 12.5 μm and so is the total length of TP material. The enhancement factor is 1.18, which is slightly higher than the enhancement factor of 1.14 found for the 2.5 μm NIM layers simulation with two bilayers.

IV. CONCLUSION

We have proposed and studied a planar thin film material concept for achieving enhanced optical power limiting. This OPL material utilizes planar NIM layers for optical focusing and conventional nonlinear two-photon absorbing material layers for limiting the optical power. We have demonstrated the viability of this material concept using numerical 2D FDTD simulations. Our analysis not only demonstrates proof-of-concept, but it also indicates that the OPL performance of this material can be readily optimized. The results presented here should stimulate research into the development of a particular class of OPL devices. Moreover, these devices represent a potential practical application for NIM metamaterials, which would leverage existing findings and motivate research in this field. Furthermore, the planar thin film nature of the proposed OPL material holds potential for low cost web-based fabrication of flexible devices, which could have significant application and impact in fields such as public safety and military technology (eye protection).

ACKNOWLEDGMENTS

This work was in part supported by a grant from the office of Vice-President for Research at the University at Buffalo and in part by the Chemistry and Life Sciences Directorate of the Air Force Office of Scientific Research.

[1] C. W. Spangler, J. Mater. Chem. **9**, 2013 (1999).
[2] Z. Yang, Appl. Phys. Lett. **86**, 061903 (2005).
[3] J. D. Bhawalkar, G. S. He, and P. N. Prasad, Rep. Prog. Phys. **59**, 1041 (1996).
[4] J. E. Ehrlich, X. L. Wu, I.-Y. S. Lee, Z.-Y. Hu, H. Röckel, S. R. Marder, and J. W. Perry, Opt. Lett. **22**, 1843 (1997).
[5] G. S. He, L. X. Yuan, N. Cheng, J. D. Bhawalkar, P. N. Prasad, L. L. Brott, S. J. Clarson, and B. A. Reinhardt, J. Opt. Soc. Am. B **14**, 1079 (1997).
[6] O.-K. Kim, K.-S. Lee, H. Y. Woo, K.-S. Kim, G. S. He, J. Swiatkiewicz, and P. N. Prasad, Chem. Mater. **12**, 284 (2000).
[7] A. Baev, P. N. Prasad, and M. Samoc, J. Chem. Phys. **122**, 224309 (2005).
[8] A. Baev, P. Norman, J. Henriksson, and H. Ågren, J. Phys. Chem. B **110**, 20912 (2006).
[9] A. Baev, P. Sałek, F. Gel'mukhanov, and H. Ågren, J. Phys. Chem. B **110**, 5370 (2006).
[10] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[11] L. Liu and S. He, Opt. Express **12**, 4835 (2004).
[12] Y. Jin and S. He, Opt. Express **13**, 4974 (2005).
[13] N. M. Litchinitser, I. R. Gabitov, A. I. Maimistov, and V. M. Shalaev, Opt. Lett. **32**, 151 (2007).
[14] I. V. Shadrivov, A. A. Zharov, and Yu. S. Kivshar, J. Opt. Soc. Am. B **23**, 529 (2006).
[15] G. D'Aguanno, N. Mattiucci, M. Scalora, and M. J. Bloemer, Phys. Rev. Lett. **93**, 213902 (2004).
[16] A. Baev, M. Samoc, P. N. Prasad, M. Krykunov, and J. Autschbach, Opt. Express **15**, 5730 (2007).
[17] A. N. Grigorenko, A. K. Geim, H. F. Gleeson, Y. Zhang, A. A. Firsov, I. Y. Khrushchev, and J. Petrovic, Nature (London) **438**, 335 (2005).
[18] V. M. Shalaev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and A. V. Kildishev, Opt. Lett. **30**, 3356 (2005).
[19] G. Dolling, C. Enkrich, M. Wegener, C. M. Soukoulis, and S. Linden, Opt. Lett. **31**, 1800 (2006).
[20] A. V. Kildishev, W. Cai, U. K. Chettiar, H.-K. Yuan, A. K. Sarychev, V. P. Drachev, and V. M. Shalaev, J. Opt. Soc. Am. B **23**, 423 (2006).
[21] G. S. He, L.-S. Tan, Q. Zheng, and P. N. Prasad, Chem. Rev. (in press).
[22] http://www.rsoftdesign.com/.