Nonlinear distributed-feedback structures as passive optical limiters

Lukasz Brzozowski and Edward H. Sargent

Department of Electrical and Computer Engineering, University of Toronto, 10 King's College Road, Toronto, Ontario, Canada, M5S 1A4

Received August 16, 1999; revised manuscript received April 17, 2000

We analyze the intensity-dependent optical response of the passive optical limiters realized with distributed-feedback structures, which consist of alternating layers of materials possessing opposite Kerr nonlinearities. By elaborating an analytical model and employing numerical simulations, we explore device performance with respect to key requirements for passive optical-limiter deployment. We prove that the proposed limiting mechanism results in complete clamping of transmitted intensity to a sensor-safe limiting value, independent of incident intensity. We provide a direct analytical result of this limiting intensity in terms of structural and material parameters. © 2000 Optical Society of America [S0740-3224(00)00508-7]

OCIS codes: 190.4360, 190.3270, 050.1950, 120.4640, 230.1150.

1. MOTIVATION

Optical limiters are prospective building blocks for a new family of nonlinear logical elements. Ideally, the limiter should have a transmittance equal to one for low-intensity radiation. The transmittance should decrease with increasing intensity to the point that the transmitted intensity is clamped at a maximum acceptable level.[1]

Passive optical limiters are commonly used as protective devices.[2–5] They can be used to protect laboratory researchers from high-intensity laser radiation,[2] safeguard military personnel from being blinded by the enemy light sources, or protect components in the devices that make use of laser light.[5] There is also a less sophisticated, but more often encountered, protective use for passive optical limiters: sunglasses.[6,7] Optical limiters are also among the elemental building blocks of the optical logic circuits.[8–11] They are prospective enablers of optical signal processing, optical sensing, and optical fiber communications.[8,12,13]

Depending on the application, passive optical limiters may be required to be broadband or narrowly spectrally discriminating. Since the spectral diversity of lasers in use is increasing, the fixed-line spectral filters cannot offer complete protection. At the present time no portion of the visible band is completely safe;[2] thus broadband protection is required. On the other hand, especially for optical signal processing and filtering, it is sometimes desirable that only a limited spectral range be blocked owing to the high intensity of the incoming radiation. It is then necessary that the limiter be wavelength selective, decreasing the transmittance of the unwanted radiation but not affecting the transmittance of the rest of the spectrum.

A reliable optical limiter must also be resistant to optical damage.[2,14] The nonlinear material that is responsible for limiting must not degrade when subjected to the high-intensity light that it is intended to block or clamp. Additionally, the limiter should be stable in the working environment. Thus it should be attached firmly to the sensor it is supposed to protect and not be affected by motion.[2] Since, especially in the protection of laboratory and military personnel, harmful radiation can be expected to come from any possible angle, the good limiter should not be angularly selective. Such characteristics cannot be expected from the one- and two-dimensional structures. Thus three-dimensional materials should be used that exhibit limiting characteristics in all directions and for arbitrary polarization.

Among most commonly used passive optical limiters are devices based on self-focusing, two-photon absorption, total internal reflection, self-defocusing, and photorefractive beam fanning.[3,4,14–16] Self-focusing and two-photon absorption rely on the absorption of the incoming radiation and as such are vulnerable to the damage of the nonlinear material.[3,4,14,16] Devices based on total internal reflection are very sensitive to alignment.[14] In self-defocusing limiters, only part of the transverse cross section of the light beam or pulse is transmitted. This leads to an output signal with a different transverse intensity profile than the incident pulse has.[4] In the photorefractive beam fanning the transmitted beam may lose its spatial and temporal coherence. In addition, high intensity weakens the photorefractive abilities of all known materials.[14]

2. APPROACH

Given the great need for good passive optical limiters, and the inadequacy of the presently available solutions, we propose herein a technique that fulfills the requirements described above. In this work we explore the basic mechanisms of our approach.

The limiters we model in this work rely upon the mechanism of nonlinear reflection rather than absorption of light. In effect, they are much less susceptible to damage than the absorption-based approach. Additionally, the proposed limiters are composed of multilayer structures, which makes them relatively easy to fabricate into any desired shape or to attach to any kind or form of surface. Once attached, such devices will not be affected by motion of the sensor they are protecting. The limiters we propose can be designed to be either highly wavelength selective or to display their limiting properties over a broad range of wavelengths.

In order to facilitate design, we solved the coupled-mode equations for the general case of a one-dimensionally periodically nonlinear medium illuminated with radiation at resonance. The medium is composed of layers with identical linear refractive indices and alternating opposite Kerr coefficients. We have obtained analytical expressions that give rapid physical insight and relate the response of the limiter to its parameters (average refractive index, Kerr coefficient, and number of layers). We corroborate this model using comprehensive and self-consistent numerical simulations. We have investigated the transmittance characteristics of the proposed limiters. During the analysis we varied such parameters as number of layers, incident intensity, the frequency of the radiation, and the strength of the nonlinear response of the optically active materials.

The presented concept of a one-dimensional limiter can be used to predict the behavior of the three-dimensional devices, made of the materials that possess the true photonic bandgap in all directions.[17] The structures that posses periodicity in all directions have previously been demonstrated experimentally. The three-dimensional PBG materials made of self-organizing structures are especially attractive owing to their relative ease of fabrication.[18,19] Such three-dimensional devices would exhibit all of the most desired limiter characteristics, including being alignment independent.

3. THEORY AND METHOD

The analyzed structures consisted of alternating layers of two different materials, each possessing Kerr nonlinearity. The index of refraction of such materials can be expressed as[20,21]

$$n = n_0 + n_{\mathrm{nl}} I, \tag{1}$$

where n_0 is the linear part, n_{nl} is Kerr coefficient, and I is the intensity of light in the medium. The coefficient n_{nl} can be either positive or negative.[22] Thus, depending on the sign of n_{nl}, the index of refraction of the given material can either increase or decrease as the intensity is varied. This fact is very important to the feasibility of the proposed limiters.

The modeling was done using the transfer matrix method[23,24] adapted to the case of nonlinear materials.[25–27] The relation between the coefficients a of the forward-propagating wave and b of the backward-propagating wave in layers j and $j + 1$ may be written[23,24] as

$$\begin{bmatrix} a_j \\ b_j \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \exp(ik_{j+1}t_{j+1})\left(1 + \dfrac{k_{j+1}}{k_j}\right) & \exp(-ik_{j+1}t_{j+1})\left(1 - \dfrac{k_{j+1}}{k_j}\right) \\ \exp(ik_{j+1}t_{j+1})\left(1 - \dfrac{k_{j+1}}{k_j}\right) & \exp(-ik_{j+1}t_{j+1})\left(1 + \dfrac{k_{j+1}}{k_j}\right) \end{bmatrix} \begin{bmatrix} a_{j+1} \\ b_{j+1} \end{bmatrix}, \tag{2}$$

in which $k = [2\pi(n_0 + n_{\mathrm{nl}} I)]/\lambda$ is the propagation constant, the intensity is given by $I = |a_n|^2 + |b_n|^2$, λ is the wavelength of the light, and t is the layer thickness. We designate the matrix-relating layers j and $j + 1$ by M_{j+1}; thus the electric field at the beginning of the multilayer structure is related to the field at the far end by

$$\begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = M_1 \times M_2 \times \ldots \times M_N \times \begin{bmatrix} a_N \\ 0 \end{bmatrix}, \tag{3}$$

where N is the total number of layers. The last b coefficient is 0 since there is no reflection from the semi-infinite space extending behind the structure. In our modeling we have assumed a value of a_N and worked backward through the structure in order to determine the incident intensity necessary to give rise to this a_N. This approach is much more computationally efficient and accurate than working forward. In order to achieve a high degree of accuracy we have divided each layer into ten virtual sublayers. The numerical simulations consisted of several iterations. To zeroth order the index of refraction in a given layer was assumed to change according to the intensity in the adjacent layer. Repeated iterations of Born approximations were carried out. In the consecutive iterations the index of refraction was modified according to the intensity present in the relevant layer rather than in the adjacent one. This procedure was performed until convergence to within 0.1% of the previous iteration was obtained.

In order to obtain an analytical expression for the evolution of forward and backward propagating waves inside the structure, we applied the coupled-mode formalism[21,24] to the case of our nonlinear periodic medium in the slowly varying envelope approximation.[20] We have assumed absorption to be negligible:

$$\begin{aligned} i\frac{\mathrm{d}A_1(z)}{\mathrm{d}z} = {} & \frac{\omega}{c}\Bigg\{ [(n_{01} - n_{02}) + (n_{\mathrm{nl}1} - n_{\mathrm{nl}2}) I(z)] \\ & \times \exp\left(-i\frac{\pi d_2}{\Lambda}\right) \frac{\sin\dfrac{\pi d_2}{\Lambda}}{\pi} \\ & \times A_2(z) \exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right]\Bigg\} \\ & - \frac{\omega}{c}[\bar{n}_{\mathrm{nl}} I(z) \times A_1(z)], \end{aligned} \tag{4}$$

$$i\frac{\mathrm{d}A_2(z)}{\mathrm{d}z} = -\frac{\omega}{c}\left\{[(n_{01} - n_{02}) + (n_{\mathrm{nl}1} - n_{\mathrm{nl}2})I(z)]\exp\left(i\frac{\pi d_2}{\Lambda}\right)\frac{\sin\frac{\pi d_2}{\Lambda}}{\pi} \times A_1(z)\exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right]\right\} + \frac{\omega}{c}[\bar{n}_{\mathrm{nl}}I(z) \times A_2(z)], \quad (5)$$

where A_1 and A_2 are the coefficients of the forward- and backward-propagating waves, respectively, ω is the frequency of the radiation. c is the speed of light in vacuum. $I(z) = |A_1(z)|^2 + |A_2(z)|^2$, k is the wave number of the light, and Λ is the period of the grating.

$$n_0 = \frac{n_{01}d_1 + n_{02}d_2}{\Lambda}, \quad \bar{n}_{\mathrm{nl}} = \frac{n_{\mathrm{nl}1}d_1 + n_{\mathrm{nl}2}d_2}{\Lambda},$$

are average linear and nonlinear refractive indices, with d_1 and d_2 being the thicknesses of the layers of first and second materials. In obtaining analytical and numerical solutions two boundary conditions were specified: $A_2(L) = 0$, which stipulates no radiation incident on the structure from the right, and $A(L) = A_{1\mathrm{out}}$.

For the special case of matched linear indices ($n_{01} = n_{02}$), opposite Kerr coefficients ($n_{\mathrm{nl}1} = -n_{\mathrm{nl}2} = n_{\mathrm{nl}}$, $\bar{n}_{\mathrm{nl}} = 0$), and equal layer thicknesses ($d_1 = d_2$), Eqs. (2) and (3) reduce to

$$\frac{\mathrm{d}A_1(z)}{\mathrm{d}z} = -\frac{\omega}{c}\frac{2n_{\mathrm{nl}}}{\pi}[|A_1(z)|^2 + |A_2(z)|^2]A_2(z)\exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right], \quad (6)$$

$$\frac{\mathrm{d}A_2(z)}{\mathrm{d}z} = -\frac{\omega}{c}\frac{2n_{\mathrm{nl}}}{\pi}[|A_1(z)|^2 + |A_2(z)|^2]A_1(z)\exp\left[-i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right]. \quad (7)$$

We solve at resonance ($2\omega n_0/c = 2\pi/\Lambda$) Eqs. (6) and (7) for $A_1(z)$ and $A_2(z)$. We obtain the following expression for the envelope of the forward-propagating wave in terms of the transmitted intensity ($I_{\mathrm{out}} = |A_{1\mathrm{out}}|^2$):

$$A_1(z) = \left\{\frac{1 + 2\exp\left[\frac{-4iI_{\mathrm{out}}n_{\mathrm{nl}}(L - z)}{\Lambda n_0}\right] + \exp\left[\frac{-8iI_{\mathrm{out}}n_{\mathrm{nl}}(L - z)}{\Lambda n_0}\right]}{2 + 2\exp\left[\frac{-8iI_{\mathrm{out}}n_{\mathrm{nl}}(L - z)}{\Lambda n_0}\right]}\right\}^{1/2} A_{1\mathrm{out}}. \quad (8)$$

Taking the squared modulus of Eq. (8) yields the expression for the evolution of the intensity across the structure:

$$i(z) = \left|\frac{1 + \cos\left[\frac{4I_{\mathrm{out}}n_{\mathrm{nl}}(L - z)}{\Lambda n_0}\right]}{2\cos\left[\frac{4I_{\mathrm{out}}n_{\mathrm{nl}}(L - z)}{\Lambda n_0}\right]}\right| I_{\mathrm{out}}. \quad (9)$$

Solving Eq. (9) for $z = 0$ yields the following relation between the transmitted and the incident intensity:

$$I_{\mathrm{in}} = \frac{1}{2}\left|\frac{1}{\cos\left(\frac{4I_{\mathrm{out}}}{a}\right)} + 1\right| I_{\mathrm{out}}, \quad (10)$$

where $a = 2n_0/Nn_{\mathrm{nl}}$ and $N = 2L/\Lambda$ is the number of layers.

Equation (10) gives I_{in} as a periodic function of I_{out}. Only solutions from the first band of this function ($4I_{\mathrm{out}}/a$ ranges from 0 to $\pi/2$) are physically possible; the remaining solutions imply a transmitted intensity larger than the incident intensity. The limiting value of I_{out} occurs when

$$I_{\mathrm{Limiting}} = \frac{\pi}{4}\frac{n_0}{Nn_{\mathrm{nl}}}. \quad (11)$$

As our numerical results obtained in Section 4 confirm, expression (11) gives the highest value of the intensity that can escape the far side of the limiter. The result constitutes an analytical proof of true, or ideal, limiting action: transmitted intensity can be guaranteed to lie below a sensor-safe value for arbitrarily intense incident radiation.

4. RESULTS AND DISCUSSION

Figure 1 and 2 best demonstrate the complete limiting behavior of the modeled structures. The indices of refraction of these two materials were, respectively, $n_1 = 1.5 + 0.01I$ and $n_2 = 1.5 - 0.01I$. The incident intensity was increased from 0 to 100. Here and throughout this work, normalized intensity is plotted in units that are reciprocal to those of n_{nl}. The response of the limiter was investigated for various numbers of layers. In all cases the thicknesses of the layers were given the values corresponding to a quarter-wave structure for an index of refraction of 1.5, for a frequency of 3×10^{14} Hz ($\lambda_0 = 1\ \mu$m).

For very low incident intensities the transmitted intensity is equal to the incident one. As the incident intensity is increased, the transmitted intensity begins to roll off, eventually saturating at the limiting value. This last

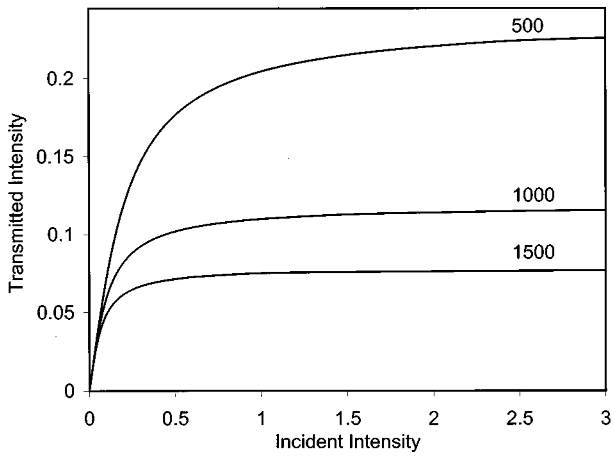

Fig. 1. Transmitted intensity as a function of incident intensity for structure with $|n_{\mathrm{nl}}| = 0.01$ for various numbers of layers. All of the limiters clamp the transmitted intensity to a limiting value.

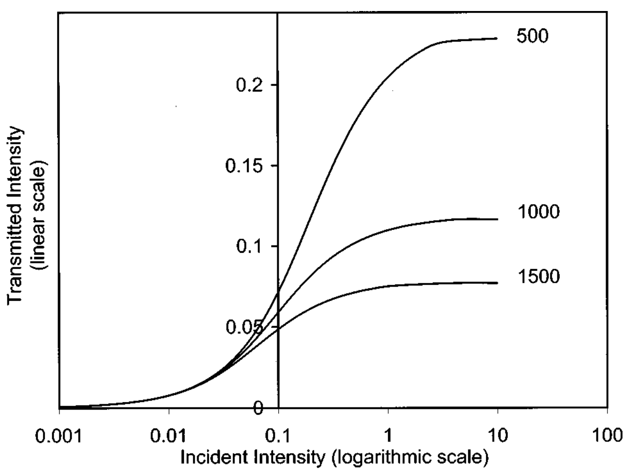

Fig. 2. Transmitted intensity is plotted as a function of incident intensity on a semi-log scale for structures with $|n_{\mathrm{nl}}| = 0.01$ for different numbers of layers. This plot illustrates the transition section between low and high incident intensities and the saturation to a limiting value.

feature is most desired from the optical limiter. We show in Figs. 1 and 2 how the value of the limiting intensity decreases with increasing numbers of layers. Thus, given a pair of materials with opposite nonlinear coefficients, one only needs to choose an appropriate number of layers, which satisfies the requirement of a specific limiting intensity. It is also very promising that the limiter does not need to have a very large number of layers in order to display an asymptotic behavior. As equation (11) proves, structures with any number of layers exhibit true optical limiting.

The response described above can be understood intuitively from a physical point of view. For very low intensity the indices of refraction of the two materials are matched. Thus the structure is transparent to the incoming light, and the transmittance is very close to 1. Increasing intensity causes the indices to change, which in effect blocks some of the light, leading to decreased transmitted intensity. As the incident intensity is increased further, the nonlinear part of the indices of refraction becomes comparable to its nonlinear part. Then, depending on the sign of n_{nl}, the index of refraction increases or decreases linearly with intensity. This causes the saturation at a given limiting intensity. Very important is the fact that the two materials have opposite Kerr characteristics. This keeps the center of the stopband at a desired frequency. In cases when only one material is nonlinearly active, a multilayer structure may display multistability.[28–32] Then, for some incident intensities there would be two or more possible transmitted intensities, which is a feature undesirable in optical limiters. In contrast with the family of limiters proposed herein, multistable structures do not necessarily exhibit saturation of the transmitted intensity to the limiting value and may exhibit chaotic behavior.[29]

We show in Fig. 3 the evolution of the refractive index across a structure made of 300 layers illuminated by normalized incident intensity equal to 1. The indices of refraction of materials and the thicknesses of the layers are the same as in Figs. 1 and 3. The incident light is chosen to have a frequency that is resonant with the structural periodicity. This plot can be used to track the decay of the intensity as the light penetrates the limiter. The first few layers experience almost all of the incident intensity, whereas the last ones see only a fraction of it. The index contrast at the beginning of the structure is much greater than at the end. The longer the structure, the more the indices of the last layers would approach the value of the average index n_0.

We display in Figs. 4 and 5 the transmittance spectra. Figure 4 shows the spectra for the same systems as in Figs. 1 and 2 for various numbers of layers. The symmetric stopband always stays at the desired frequency, which is a very significant characteristic of a limiter. As mentioned before, such behavior is caused by the opposite nonlinear properties of the two materials. Also, as the number of the layers in the structure is increased, the stopband gets deeper and sharper. We show in Fig. 5 the spectra for 300 layers with $n_{\mathrm{nl}} = \pm 0.01$ for incident intensities of 0.5, 1, and 3. This plot again illustrates the limiting behavior. As the strength of the incident intensity is increased, the transmittance decreases, and the width

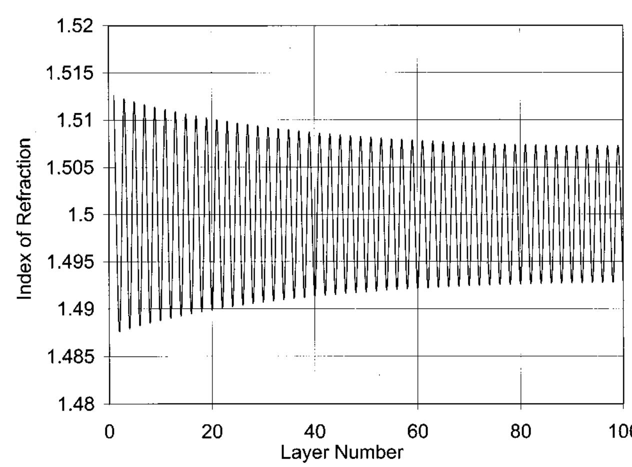

Fig. 3. Indices of refraction are plotted across the structure of 300 layers with $|n_{\mathrm{nl}}| = 0.01$. The decay of the intensity across the structure is thus demonstrated.

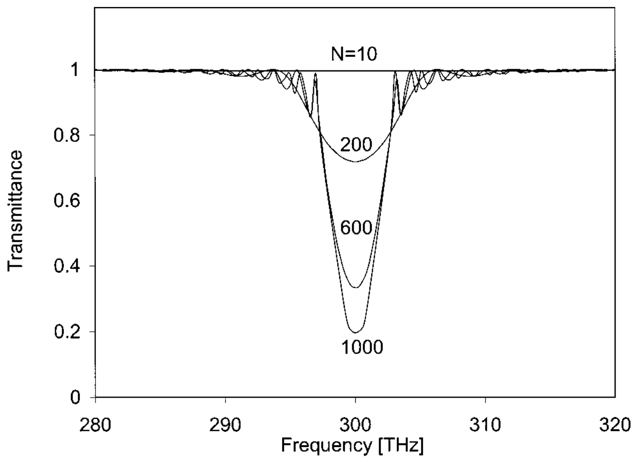

Fig. 4. Evolution of transmittance spectra for structures with $|n_{\mathrm{nl}}| = 0.01$ with increasing number of layers is shown. The nonlinear behavior of the limiter is responsible for the formation of a stopband at the desired frequency.

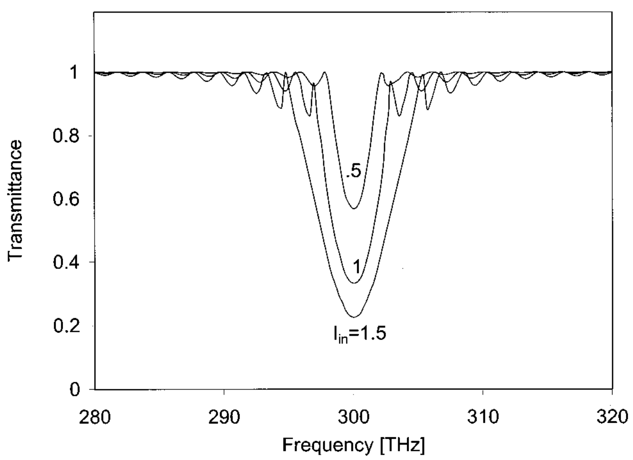

Fig. 5. Plot demonstrates the evolution of the transmittance spectra made of 300 layers with $|n_{\mathrm{nl}}| = 0.01$ as a function of increased incident intensity. As the incident intensity is increased, the stopband becomes deeper and wider.

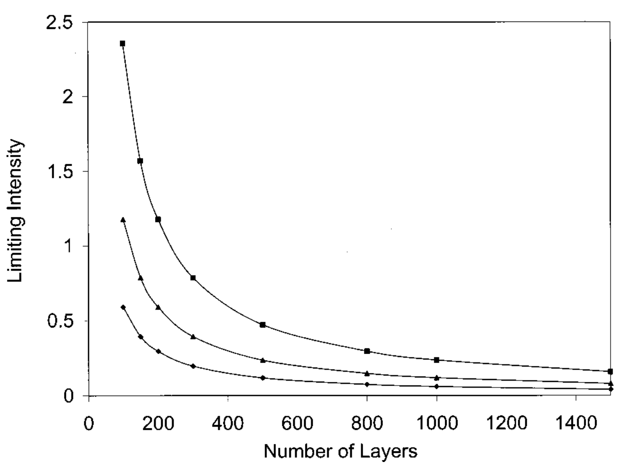

Fig. 6. Values of limiting intensities are plotted as a function of the number of layers for n_{nl} values of ± 0.005, ± 0.01, and ± 0.02. The values obtained from numerical calculations, shown on the plot as squares, triangles, and diamonds, follow exactly the curves predicted by the analytical model.

of the stopband gets larger. Increasing the incident intensity has the same effect as increasing the value of n_{nl}, since it is the product of those two, which changes the refractive index.

We show in Fig. 6 the critical intensities for structures illuminated using light at the center of the stopband, as a function of the number of layers for $|n_{\mathrm{nl}}|$ values of 0.005, 0.01, and 0.02. The curves obtained from Eq. (11) were plotted for the same cases. The points obtained from the numerical simulations appear in the predicted places on these curves. Thus the highest possible intensity that will be transmitted by a given structure is inversely proportional to the nonlinear strength n_{nl} and number of layers N, but directly proportional to n_0, the average index of refraction of the two materials used.

Low-threshold implementations of the devices explored herein will rely on the use of materials with large Kerr nonlinearities. Recently, highly nonlinear materials have been reported with n_2 ranging from $1 \times 10^{-10}\,\mathrm{cm}^2/\mathrm{W}$ to as high as $1 \times 10^{-6}\,\mathrm{cm}^2/\mathrm{W}$ with response times of picoseconds or better.[13,33–35] A 1-mm-long limiter operating on 0.532-μm light would, using these materials, achieve a limiting intensity of $1 \times 10^6\,\mathrm{W/cm}^2$ to as low as $1 \times 10^2\,\mathrm{W/cm}^2$. These intensities are many orders of magnitude lower than reported for reverse saturable absorption-based limiters of the same length and operating at the same wavelength. These typically require incident intensity of the order of 0.1 $\mathrm{GW/cm}^2$ and do not show full clamping of the transmitted intensity.[36–38]

5. CONCLUSIONS

Aided by an analytical model and numerical simulations, we have analyzed the response of limiters that address all the key requirements of their field. Our devices are based on multilayer structures composed of materials with opposite nonlinear Kerr coefficients. Such limiters exhibit the key properties desired of ideal optical limiters. The transmitted intensity is clamped at a certain value. Knowing the maximum safe value for a given case, the limiter can be accordingly designed owing to the derived relationship between the limiting intensity and the parameters of the structure. The limiters that we have modeled rely on the reflection rather than absorption, which makes them much less susceptible to damage by high intensity. The extension of the one-dimensional design to three-dimensional structures can be an origin of ideal, alignment-insensitive passive optical limiters. Once created, such devices would have countless uses in sensor protection and optical logic.

ACKNOWLEDGMENT

The authors thank Mathieu Allard, Emanuel Istrate, and Erik Johnson for valued discussions.

REFERENCES

1. H. B. Lin, R. J. Tonucci, and A. J. Campillo, "Two-dimensional photonic bandgap optical limiters in the visible," Opt. Lett. **23**, 94–96 (1998).

2. R. C. Hollins, "Overview of research on nonlinear optical limiters at DERA (Defence Evaluation & Research Agency)," in *Photosensitive Optical Materials and Devices II*, M. P. Andrews, ed., Proc. SPIE **3282**, 2–8 (1988).
3. T. Xia, D. J. Hagan, A. Dogariu, A. A. Said, and E. W. Van Stryland, "Optimization of optical limiting devices based on excited-state absorption," Appl. Opt. **36**, 4110–4122 (1997).
4. I. C. Khoo, M. Wood, and B. D. Guenther, "Nonlinear liquid crystal optical fiber array for all-optical switching/limiting," in *LEOS '96 9th Annual Meeting* (IEEE, Piscataway, N.J., 1996), Vol. 2, pp. 211–212.
5. P. Miles, "Bottleneck optical pulse limiters revisited," Appl. Opt. **38**, 566–570 (1999).
6. J. S. Werner, "Children's sunglasses: caveat emptor," Optom. Vision Sci. **68**, 318–320 (1991).
7. S. M. Luria, "Preferred density of sunglasses," Am. J. Optom. Physiol. Opt. **61**, 397–402 (1984).
8. P. N. Prasad, "Design, ultrastructure, and dynamics of nonlinear optical effects in polymeric thin films," in *Electroactive Polymer Materials: State-of-the-Art Review of Conductive Polymers*, A. Wirsén, ed. (Technomic, Lancaster, Pa., 1987), pp. 41–67.
9. P. N. Prasad and D. J. Williams, *Introduction to Nonlinear Optical Effects in Molecules and Polymers* (Wiley, New York, 1991).
10. N. S. Pate, L. Hall, L. Katherine, and K. A. Raushenbach, "Interferometric all-optical switches for ultrafast signal processing," Appl. Opt. **27**, 2831–2842 (1998).
11. P. Tran, "All-optical switching with a nonlinear chiral photonic bandgap structure," J. Opt. Soc. Am. B **16**, 70–73 (1999).
12. M. Scolara, J. P. Dowling, C. M. Bowden, and M. J. Bloemer, "Optical limiting and switching of ultrashort pulses in nonlinear photonic bandgap materials," Phys. Rev. Lett. **73**, 1368–1371 (1994).
13. R. Rangel-Rojo, S. Yamada, S. Matsuda, and H. D. Yankelevich, "Large near-resonance third-order nonlinearity in an azobenzene-functionalized polymer film," Appl. Phys. Lett. **72**, 1021–1023 (1998).
14. G. L. Wood, W. W. Clark III, M. J. Miller, G. J. Salamo, and E. J. Sharp, "Evaluation of passive optical limiters and switches," in *Materials for Optical Switches, Isolators, and Limiters*, M. J. Soileau, ed., Proc. SPIE **1105**, 154–181 (1989).
15. R. Bozio, M. Meneghetti, R. Signorini, M. Maggini, G. Scorrano, M. Prato, G. Brusatin, M. Guglielmi, "Optical limiting of fullerene derivatives embedded in sol-gel materials," in *Photoactive Organic Materials Science and Applications*, F. Kajzer, ed., NATO ASI Ser. B **572**, 159–174 (1996).
16. J. A. Hermann, P. B. Chapple, J. Staromlynska, and P. J. Wilson, "Design criteria for optical power limiters," in *Nonlinear Optical Materials for Switching and Limiting*, M. J. Soileau, ed., Proc. SPIE **2229**, 167–178 (1994).
17. S. John, "The localization of light," in *Photonics Band Gaps and Localization*, C. M. Soukoulis, ed. (Plenum, New York, 1993), pp. 1–22.
18. K. Ishizu, T. Ikemoto, and A. Ichimure, "Architecture of polymeric superstructures formed by locking cubic lattices of core-shell polymer microspheres," Polymer **39**, 449–454 (1998).
19. K. Ishizu, F. Naruse, and R. Saito, "The aggregation behavior of core-shell type polymer microspheres," Polymer **35**, 2329–2334 (1994).
20. B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991).
21. G. I. Stegeman, C. Liao, and H. G. Winful, "Distributed feedback bistability in channel waveguides," *Optical Bistability 2*, C. M. Bowden, H. M. Gibbs, and S. L. McCall, eds. (Plenum, New York, 1983), pp. 389–396.
22. H. S. Nalwa and S. Miyata, *Nonlinear Optics of Organic Molecules and Polymers* (CRC, Boca Raton, Fla., 1997).
23. P. Yeh, *Optical Waves in Layered Media* (Wiley, New York, 1988).
24. A. Yarif and P. Yeh, *Optical Waves in Crystals* (Wiley, New York, 1984).
25. J. He and M. Cada, "Combined distributed feedback and Fabry–Perot structures with a phase-matching layer for bistable devices," Appl. Phys. Lett. **61**, 2150–2152 (1992).
26. M. Bertolotti, P. Masciulli, P. Ranieri, and C. Sibilia, "Optical bistability in nonlinear Cantor corrugated waveguide," J. Opt. Soc. Am. B **13**, 1517–1525 (1996).
27. L. Caleo, C. Sibilia, P. Masciulli, and M. Bertlotti, "Nonlinear-optical filters based on the cascading second-order effect," J. Opt. Soc. Am. B **14**, 2315–2324 (1997).
28. H. G. Winful, J. H. Marburger, and E. Garmire, "Theory of bistability in nonlinear distributed feedback structure," Appl. Phys. Lett. **35**, 379–381 (1979).
29. H. G. Winful and G. D. Cooperman, "Self-pulsing and chaos in distributed feedback bistable optical devices," Appl. Phys. Lett. **40**, 298–300 (1982).
30. C.-X. Shi, "Optical bistability in reflective fiber grating," IEEE J. Quantum Electron. **31**, 2037–2043 (1995).
31. H. M. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic, Orlando, 1985).
32. S. Dubovitsky and W. H. Steier, "Analysis of optical bistability in a nonlinear coupled resonator," IEEE J. Quantum Electron. **28**, 585–589 (1992).
33. Z. X. Zhang, W. Qiu, E. Y. B. Pun, P. S. Chang, and Y. Q. Shen, "Doped polymer films with high nonlinear refractive indices," Electron. Lett. **32**, 129–130 (1996).
34. C. R. Mendoca, M. M. Costa, J. A. Giacometti, F. D. Nunes, and S. C. Zilio, "Nonlinear refractive indices of polyesterene films doped with azobenzene dye Disperse Red 1," Electron. Lett. **34**, 116–117 (1998).
35. E. W. Van Stryland and M. Shei-Bahae, "Z-scan," in *Characterization Techniques and Tabulations for Organic Nonlinear Optical Materials*, M. G. Kuzyk and C. W. Dirk, eds. (Marcel Dekker, New York, 1998), pp. 655–692.
36. F. J. Aranda, C. F. Cheng, D. V. G. L. N. Rao, J. A. Akkara, D. L. Kaplan, and J. F. Roach, "Two-photon absorption in polybenzine," in *Materials for Optical Limiting*, R. Crane, K. Lewis, E. Van Stryland, and M. Khoshnevisan, eds. (Materials Research Society, Pittsburgh, Pa., 1994), pp. 185–194.
37. P. A. Fleiz, R. L. Sutherland, and T. J. Bunning, "Z-scan measurements of molten diphenylbuandiene in the isotropic liquid state," in *Materials for Optical Limiting*, R. Crane, K. Lewis, E. Van Stryland, and M. Khoshnevisan, eds. (Materials Research Society, Pittsburgh Pa., 1994), pp. 211–216.
38. M. Brunel, F. Chaput, S. A. Vindogradov, B. Campagne, M. Canva, J-P. Boilot, and A. Brun, "Reverse saturable absorption in organically-doped xerogels," in *Materials for Optical Limiting II*, R. Sutherland, R. Pachter, P. Hood, D. Hagan, K. Lewis, and J. Perry, eds. (Materials Research Society, Pittsburgh, Pa., 1997), pp. 97–102.