# Nonlinear Pulse Switching Using Long-Period Fiber Gratings

V. E. Perlin and H. G. Winful

***Abstract*—We show that the intensity required to achieve all-optical switching in long-period fiber gratings can be reduced by orders of magnitude through the use of uniform phase-shifting regions between gratings. Predicted switching intensities are of the order 100 MW/cm$^2$ compared to 10 GW/cm$^2$ for normal device configuration.**

***Index Terms*—Gratings, nonlinear wave propagation, optical coupling, optical fiber cladding, optical fiber switches, optical pulses.**

## I. Introduction

THE USE of long period fiber gratings (LPFG's) for nonlinear switching of short pulses has been recently proposed and experimentally demonstrated by Kutz *et al.* [1]. The LPFG provides coupling between copropagating modes in the fiber, which in [1] are the core and cladding modes. The intensity dependence of the refractive index can be used to tune the coupling resonance, which makes the LPFG act as a nonlinear directional coupler whose transmission depends on input intensity. This allows the all-optical discrimination of the intense parts of a signal from the weak parts, and can be utilized in various optical devices, such as optical switches, shutters, Mach–Zehnder interferometers, modelocked fiber lasers, and WDM components in optical communication systems. The important feature of this LPFG-coupler that makes it attractive for future applications is its simplicity: it is polarization independent and does not require any prisms or other optical elements. The only thing required, except for the LPFG itself, is the means for stripping the cladding modes at the output end of the device. However, this LPFG-coupler has a crucial disadvantage: due to effects of detuning and walkoff (which will be discussed below) between coupled modes, the coupling length for normal device operation should be very small (of the order of few centimeters) and, therefore, the intensities required to obtain nonlinear action are extremely high. In the experimental work [1] the nonlinear switching occurred at peak pulse intensities of the order of 10 GW/cm$^2$ which is unacceptable for communication applications.

Another scheme for nonlinear switching is to use dual-core fiber, where the coupling occurs between the two identical parallel cores [2]. In this case the coupled modes are identical so there is no detuning and walkoff between them, and the coupling length can be taken in principle rather large thus allowing nonlinear operation at low intensities. However, this is difficult to achieve in practice.

In this paper we propose and analyze a device, which is free of this disadvantage. The idea is to make the coupling via LPFG distributed over a long distance, which will obviate the necessity for too high intensities and the necessity for parallel identical cores. This decreases the peak intensities required for nonlinear action by orders of magnitude, compared with those reported in [1], while maintaining the practical feasibility and simplicity.

## II. Principle of Operation

In LPFG, the periodic perturbation of the refractive index of the medium serves to satisfy the phase-matching condition between the modes which have slightly different propagation constants

$$\beta_{\rm core} - \beta_{\rm clad} = \frac{2\pi}{\Lambda} \tag{1}$$

where $\beta_{\rm core}$, and $\beta_{\rm clad}$ are these propagation constants (we can consider two arbitrary copropagating modes with nonzero overlap), and $\Lambda$ is the grating period which is much longer than the wavelength, and can be of the order of hundreds of microns [3]. Due to the difference in wavelength dependences of propagation constants $\beta_{\rm core}$ and $\beta_{\rm clad}$ the phase matching condition (1) for the two modes can be satisfied only in some narrow wavelength interval. The bandwidth of the LPFG-coupler is thus inversely proportional to the difference between derivatives $\partial\beta_{\rm core}/\partial\lambda - \partial\beta_{\rm clad}/\partial\lambda$. It is well approximated by [3]

$$\Delta\lambda = \frac{0.8\lambda^2}{L\Delta n_g} \tag{2}$$

where $\Delta n_g$ is the difference in group indices of these modes and $L$ is the length of LPFG. The copropagating core and cladding modes can be described by the system of two coupled mode equations [1], which can be conveniently represented in the dimensionless soliton units [2]

$$i\left(\frac{\partial u}{\partial \xi} - \frac{\Delta V_g}{2}\frac{\partial u}{\partial \tau}\right) + \frac{1}{2}\frac{\partial^2 u}{\partial \tau^2} + \kappa v + |u|^2 u = 0 \tag{3a}$$

$$i\left(\frac{\partial v}{\partial \xi} + \frac{\Delta V_g}{2}\frac{\partial v}{\partial \tau}\right) + \frac{\beta}{2}\frac{\partial^2 u}{\partial \tau^2} + \kappa u = 0 \tag{3b}$$

where $u$ and $v$ are the field intensities in core and cladding modes, respectively. The dimensionless time is

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The authors are with the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109 USA.

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$\tau = (t - z/V_g)/T_0$, where $T_0$ is characteristic pulse width and $V_g$ is the arithmetical average of the group velocities of the two modes. The dimensionless distance is $\xi = z/L_D$, with dispersion length $L_D = T_0^2/|\beta_2|$, where $\beta_2$ is the group velocity dispersion parameter. The parameter $\Delta V_g$ is the dimensionless difference between group velocities of the two modes. The coupling constant $\kappa$ is proportional to the ultraviolet induced change of refractive index in the grating and to the overlap between the two coupled modes. Here we assume that the modes are perfectly matched [i.e., the condition (1) is exactly satisfied at the central frequency of the pulse]. The effect of detuning for the very short (broadband) pulses can be taken into account in (3) by introducing a wavelength dependent coupling constant $\kappa = \kappa(\omega)$. We have neglected here the effect of cross-phase modulation and effect of self-phase modulation for the cladding mode, which are unimportant due to large effective area of the cladding mode. Parameter $\beta$ expresses the fact that the dispersion can be different for two modes.

In the linear case (low intensities) and in the absence of walkoff, the energy is periodically exchanged between the two modes. If we choose the length of LPFG to be exactly one-half beat-length ($L = \pi/2\kappa$) [1], then the input pulse in one mode will be completely coupled (switched) to the other mode. At the same time the high intensity pulse (or the high intensity parts of the pulse) will be detuned due to the intensity dependent phase shift [effect of self-phase modulation (SPM), the last terms in (3)]. Thus, the LPFG will act as nonlinear switch. In order for SPM to play a significant role, the nonlinear phase shift at the coupling length should be of appreciable value

$$\Delta\phi_{NL} = \frac{2\pi}{\lambda} n_2 I L \sim 1. \tag{3}$$

Here $n_2$ is the nonlinear refractive index of the medium ($n = n_0 + n_2 I$) and $L$ is the coupling length. The typical length of LPFG required for complete switching is $L \sim$ 1–5 cm [3]. For the standard fiber with nonlinear refractive index $n_2 = 3.2 \times 10^{-16}$ cm$^2$/W and for the LPFG length $L = 5$ cm this gives the condition for the required intensity $I \sim 15$ GW/cm$^2$. But from the condition (3) we see that the required intensity is inversely proportional to the length of the device. Thus, if we take for example the LPFG 50 m long we get quite achievable required intensity of 15 MW/cm$^2$. However, this is not a practical solution because of the effects of walkoff and detuning. Indeed, suppose the difference between the group indices of the two modes $\Delta n_g \sim 0.03$. Then for the actual wavelength $\lambda = 1.55\,\mu$m we get from (1) the bandwidth $\Delta\lambda =$ 1–5 nm. Thus the LPFG coupler can work only for pulses much longer than 1 ns (if $L = 50$ m), so that their bandwidth $\Delta\omega = 2\pi/T_0$ is much smaller than that of LPFG, and the wavelength dependence of the coupling constant can be neglected. Otherwise, complete switching is impossible, because different frequency components of the signal will have different half-beat lengths. The other limitation on duration of the pulses comes from the effect of walkoff. The pulses propagating in the core and cladding over the distance of $\Delta x$ will be separated in time by $\Delta t = \Delta n_g \Delta x/c$ . This time $\Delta t$ (when $\Delta x$ is the length of LPFG) should be much smaller than the pulse duration in order to get high-quality coupling. This gives again the condition $T_0 \gg 1$ ns for $L = 50$ m. Thus, the gratings this long can work only for pulses with duration of tens of nanoseconds, which is not that desirable.

We propose the following idea. Let $L_0$ be length of LPFG required for complete linear switching. Consider two LPFG's with total length equal to $L_0$, say $\alpha L_0$ and $(1-\alpha)L_0$, ($\alpha < 1$), separated by large distance $D$ along the unperturbed fiber. Then, at the first grating, the input pulse in one of the two modes will only be partly coupled to the other mode. For the linear coupling the fraction of pulse energy coupled will be $\sin^2(\pi\alpha/2)$ [2]. Suppose there is no walkoff in the system. Then, after the first LPFG the two parts of the initial pulse—one in the core—the other in the cladding mode, will propagate independently of each other (not coupled) and get to the second LPFG simultaneously. The relative phase acquired by these two pulses after the propagation between the LPFG's is

$$\Delta\phi_{\text{core-clad}} = (\beta_{\text{core}} - \beta_{\text{clad}})D + n_2(I_{\text{core}}\beta_{\text{core}} - I_{\text{clad}}\beta_{\text{clad}})D \tag{4}$$

where the second term represents nonlinear phase shift. It is well known from the theory of coupled modes, that the direction of energy flow in the coupler depends on relative phase of the input signals. If the acquired relative phase (4) is zero (or $2\pi k$, where $k$ is an integer) then the coupling process started at the first LPFG will continue at the second, as if there was no propagation between them. Recalling the fact that the total length of the two gratings is $L_0$ we see that complete switching occurs in this case. From (4) we see that this complete switching can be detuned by intensities of the order of $(n_2\beta D)^{-1}$, and since $D$ can be large, the required intensities are moderate. For such intensities the nonlinearity does not play a role in the length of LPFG (if $L_0 \ll D$), so the coupling is linear.

The above scheme assumes, that there is no walkoff between the two modes. In fact the walkoff can be as large as 1 ps per 1 cm of propagation (as for $\Delta n_g = 0.03$). Thus, after some propagation distance the two parts of the short signal will be completely separated in time. This is taken into account in the following scheme to compensate the walkoff. We introduce two auxiliary LPFG's of length $L_0$ each, between the two functional LPFG's, discussed above. If the pulses arrive at each of them separately, they will be completely switched to the opposite modes. After two switchings they will return into their original modes. If these two LPFG's are placed exactly at the distance $D/2$ from each other, then each of the two pulses will propagate the distance $D/2$ in the core mode and the same distance $D/2$ in the cladding mode. Thus, they will obviously arrive at the last (functional) LPFG simultaneously. The relative phase shift in this scheme is given by (5) at the bottom of the page where the index 1 refers to the pulse which stays in core after the first LPFG, and the index 2 refers to its coupled counterpart. Here we get automatically the acquired relative phase for low intensity pulses to be zero, while for high intensities the pulses are detuned, unless $I_1 = I_2$ (i.e., we should take the functional LPFG's with different lengths, $\alpha \neq 1/2$). The requirement for accuracy here is quite strict: the deviation $\Delta D$ of the distances discussed here from $D/2$ should be much smaller than the period of LPFG $\Lambda$ [from (1)] so that $(\beta_{\text{core}} - \beta_{\text{clad}})\Delta D \ll 1$. In the next section we study the performance of this device numerically.

## III. Numerical Simulations

The proposed device configuration is shown in Fig. 1. The four LPFG of lengths $\alpha L_0$, $L_0$, $L_0$, and $(1-\alpha)L_0$ are separated by the distances $D/4$, $D/2$, and $D/4$. We choose the first and last of them to be $D/4$ to ensure maximum possible walkoff separation of the two pulses on both of the two auxiliary gratings, which ultimately allows the device to work on longer pulses. The parameter $\alpha$ is chosen from the following considerations. The intensity dependent phase shift (5) is proportional to the difference of pulse energies in the two modes. This suggests taking $\alpha$ as far from 1/2 as possible. On the other hand, if one of the pulses is much weaker the other, it cannot substantially affect the direction of energy flow during coupling. The energy will flow from much stronger mode to the weaker one. So, the closer $\alpha$ is to the value 1/2, the better (steeper) is the switching characteristic of the device, but the larger is the required intensity. With these tradeoffs in mind, we choose somewhat optimal value of $\alpha = 1/3$, which corresponds to the coupling of 25% of energy, i.e., $I_1 - I_2 = 0.75I_0 - 0.25I_0 = 0.5I_0$. The other parameters of the system, which are taken to be practical, are the following. The wavelength $\lambda = 1.55\,\mu$m, the GVD parameter $\beta_2 = -20$ ps$^2$/km, the effective fiber area for the core mode $A_{\rm eff} = 60\,\mu{\rm m}^2$. The effective area for the cladding mode is much larger, thus the nonlinear phase shift for cladding mode can be neglected. The LPFG length for complete coupling $L_0 = 5$ cm, the difference between group indices $\Delta n_g = 0.03$ as discussed above. The total length of the device is taken to be $D = 125$ m. The input pulses of the soliton profile $u(\xi = 0, \tau) = u_0\,{\rm sech}(\tau/T_0)$ with different amplitudes $u_0$ and durations $T_{\rm FWHM} = 1.76T_0$ are launched into the core mode. Parameter $\beta$ in (3) is taken to be 1, meaning that dispersion is the same for two modes. In fact, dispersion does not play significant role in this scheme. For pulse duration $T_0 = 10$ ps the dispersion length $L_D = T_0^2/|\beta_2| = 5$ km is much larger than the device length.

The device performance is simulated numerically by solution of the system of two coupled nonlinear Schroedinger equations (3) using the standard split-step Fourier technique. The pulse duration in study was in the range $T_0 = 10$–300 ps. Although, some kind of nonlinear action (the dependence of transmission coefficient on input intensity) was observed even for 5 ps pulses, the quality of the output for such short pulses is extremely poor (because of walkoff). It resembles the noise rather than the pulse. Pulses longer than 300 ps are not well separated in the distance $D/4$, thus no auxiliary switching is possible. In the range 10–300 ps the behavior of the device is in accordance with our predictions, and almost independent of pulse duration. The propagation of a $T_0 = 50$ ps pulse with the peak intensity $I = 80$ MW/cm$^2$ through the device is shown in Fig. 2. The output pulse has a symmetric shape, has slightly lower peak intensity and is much shorter than the input pulse. Almost the same pattern of propagation is shown by the pulse with the same duration $T_0 = 50$ ps and smaller peak intensity $I = 20$ MW/cm$^2$ (see Fig. 3). The only difference from previous case occurs at

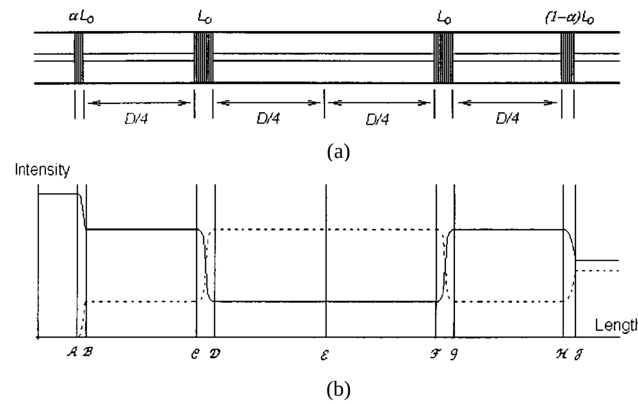



Fig. 1. (a) The proposed switch design and (b) pulse energy in the core mode (solid line) and cladding mode (dashed line) along the switch.

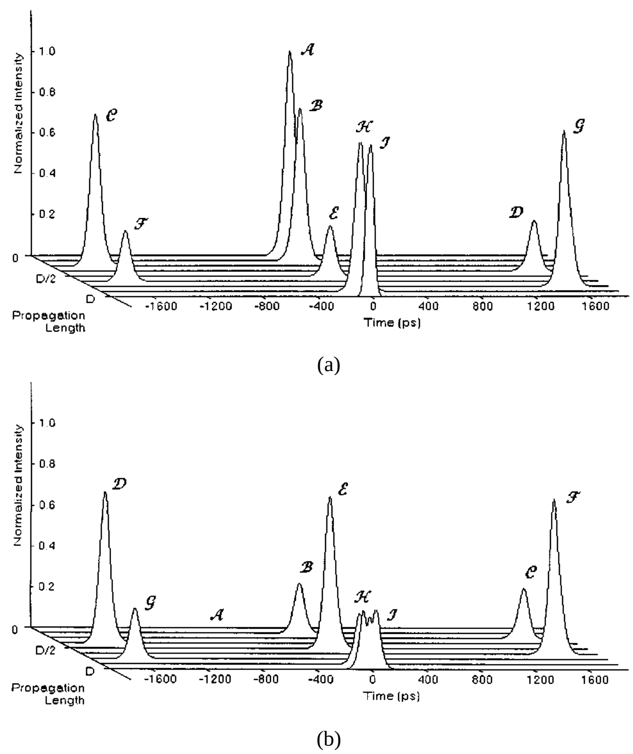
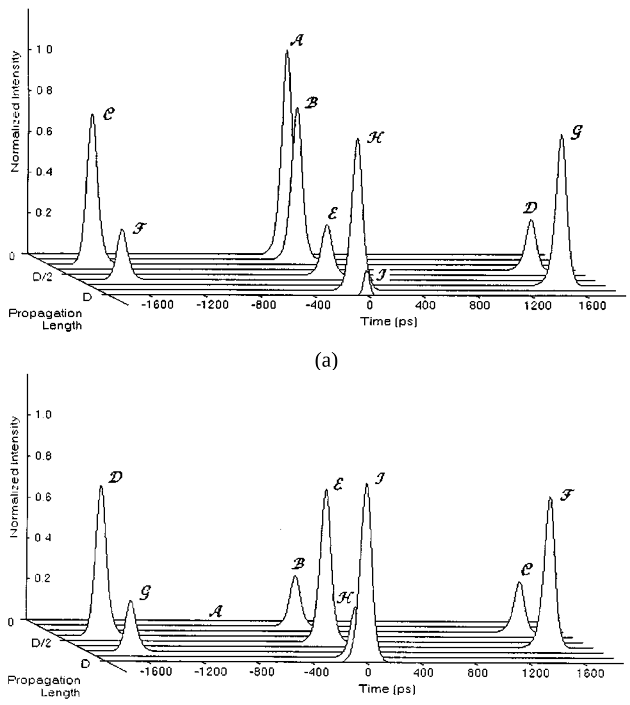



Fig. 2. Propagation of a pulse with peak input intensity 80 MW/cm$^2$: (a) in core and (b) in cladding mode. The pulses are shown before and after each LPFG and in the middle of the device. The letters A–J correspond to those in Fig. 1(b) and describe the current position of the pulse along the device. At the auxiliary LPFG's the pulses are separated because of walkoff and are switched completely to the opposite modes. At the output end the intense pulse stays in the core.

$$\Delta\phi_{\text{core-clad}} = \frac{n_2(I_{1,\,\rm core}\beta_{\rm core} + I_{1,\,\rm clad}\beta_{\rm clad} - I_{2,\,\rm core}\beta_{\rm core} - I_{2,\,\rm clad}\beta_{\rm clad})D}{2} \tag{5}$$




(a)

(b)

Fig. 3. Propagation of a pulse with peak input intensity 20 MW/cm$^2$: (a) in core and (b) in cladding mode. The pulses are shown before and after each LPFG and in the middle of the device. The letters A–J correspond to those in Fig. 1(b) and describe the current position of the pulse along the device. At the auxiliary LPFG's the pulses are separated by because of walkoff and are switched completely to the opposite modes. The low intensity input pulse is almost completely switched to the cladding mode.

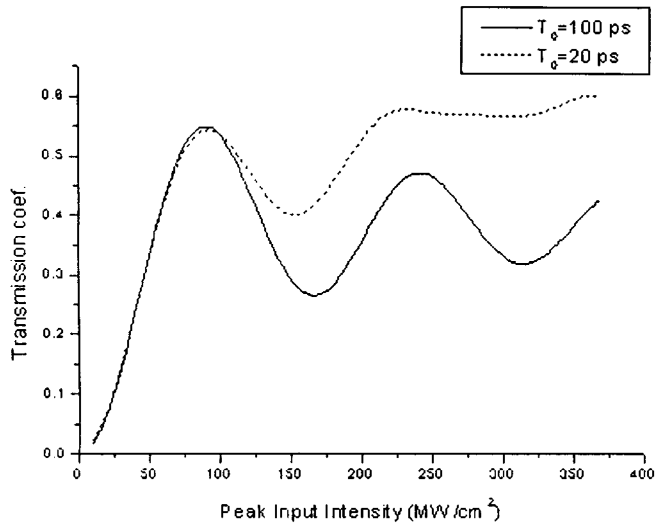



Fig. 4. Dependence of the transmission coefficient on the input intensity for two values of the pulse duration.

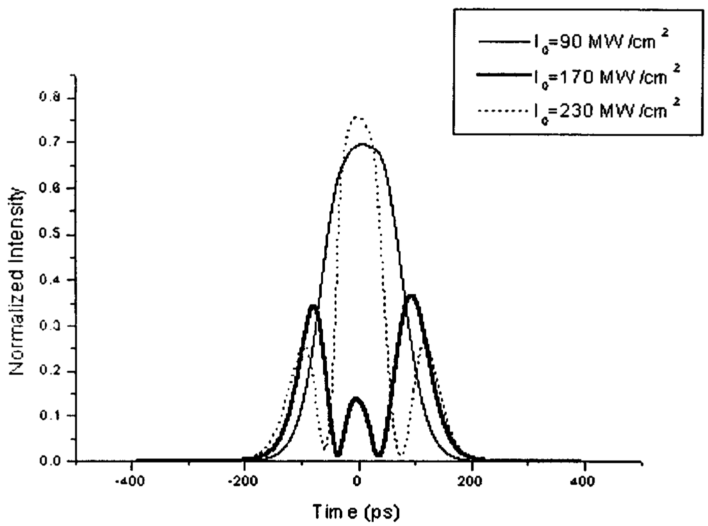



Fig. 5. The output pulse profiles for different values of input intensities. Parts of the pulse with intensities close to an odd multiple of 80 MW/cm$^2$ remain in the core, while parts with intensities close to an even multiple of 80 MW/cm$^2$ are switched to cladding.

the last LPFG: the pulses have no phase shift between them and continue their almost unperturbed coupling, started at the first LPFG. Thus a very weak output pulse stays in the core. Most of the energy is switched to the cladding mode and is to be stripped away.

The dependence of the transmission coefficient (the ratio of the total energy at the output of the core and the input) on the peak input intensity for two different values of $T_0$ is presented in the Fig. 4. The transmission coefficient grows from zero at low intensities until it reaches the maximum value of about 0.6 at intensities near 80 MW/cm$^2$, and then oscillates with the same half-period of 80 MW/cm$^2$. Maxima of this oscillation correspond to the case where the central part of the pulse is detuned from the coupling resonance and stays in the core, while minima correspond to the central part coupled to the cladding (Fig. 5). Obviously, this oscillation has higher amplitude for longer pulses.

Substantial improvement in the switching characteristics of the device can be achieved using a multiple-pass configuration, where the output pulse from one switch serves as an input pulse for the next switch. The output pulse is narrower than the input one, but if its duration is still larger than the walkoff limit of about 10 ps, then it can serve again as an input. Since the maximum switch transmission is about 0.5–0.6, the transmission in multiple-pass configuration will decrease with increasing number of passes. This, however, can be compensated by subsequent pulse amplification, while very strong discrimination against weak pulses is achieved. The transmission of the 2- and 3-pass device for initial pulse width of 100 ps is shown on Fig. 6. As expected, the more passes there are, the steeper the intensity dependence of transmission coefficient is. As an example, after three passes the transmission coeffiicient for input intensity $I = 90$ MW/cm$^2$ is 230 times larger than for $I = 50$ MW/cm$^2$.

## IV. Discussion

We have proposed and analyzed a device which utilizes long-period fiber gratings to achieve intensity dependent switching between copropagating core and cladding modes in the fiber. The LPFG by itself requires extremely high intensities to produce intensity dependent action since it is very short. We proposed to distribute the LPFG coupling over much longer distances, so that the required intensities which are inversely proportional to the device length, are decreased. The walkoff

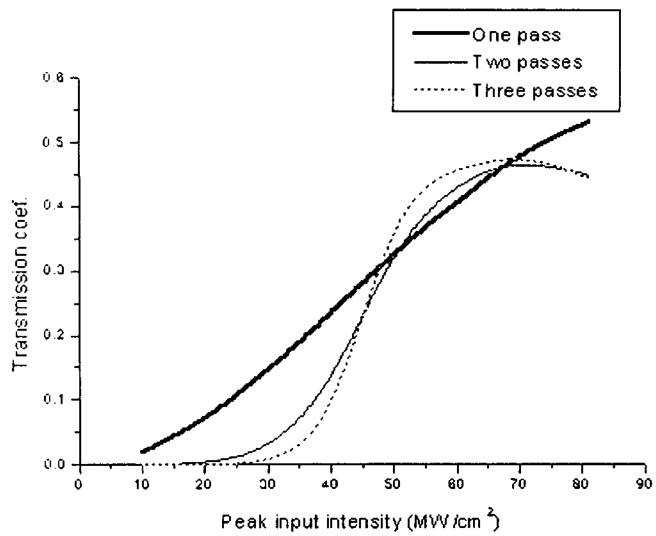



Fig. 6. Intensity dependence of the transmission coefficient for the multiple-pass device configuration.

problem is solved by a simple scheme. The length of the device, however, is limited in practice by other several factors. One of these factors—precise placement of gratings is pointed out in Section II. Another factor, which is understood as the most critical for the proposed device feasibility—is losses in the cladding mode. To our knowledge, in fibers available at the present time these losses are too high to make propagation over tens of meters in a cladding mode possible. Thus the switch can work only if cladding losses are minimized or, for example, compensated by simultaneous distributed amplification. However, the proposed idea should not necessarily be limited to cladding modes. The LPFG can be used to couple two different polarization modes or any two different order core modes. The analysis and simulations presented above can be applied to these cases with a few changes, such as inclusion of cross-phase modulation. In general, if the signal is split at the first LPFG so that the pulse energies are different in two modes, these two pulses will acquire different nonlinear phase shift upon propagation to the last LPFG and intensity dependent transmission will occur. The proposed scheme can be used in various optical applications.

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**V. E. Perlin**, photograph and biography not available at the time of publication.

**H. G. Winful**, photograph and biography not available at the time of publication.