measurements and D. C. Craft for assistance in laser characterization. They acknowledge R. L. Hartman for discussions and P. J. Anthony for support and discussions.

[1]W. T. Tsang, Appl. Phys. Lett. **38**, 204 (1981); **40**, 217 (1982).
[2]S. D. Harsee, M. Baldy, P. Assent, B. de Cremoux, and J. P. Duchemin, Electron. Lett. **18**, 1095 (1982).
[3]N. Holonyak, R. M. Kolbas, R. D. Dupuis, and P. D. Dapkus, IEEE J. Quantum Electron. **QE-16**, 170 (1980).
[4]N. K. Dutta, J. Appl. Phys. **53**, 7211 (1982); **54**, 1236 (1983).
[5]A. Sugimura, Appl. Phys. Lett. **42**, 17 (1983); IEEE J. Quantum Electron. **QE-19**, 932 (1983).
[6]L. C. Chiu and A. Yariv, IEEE J. Quantum Electron. **QE-18**, 1406 (1982).
[7]N. K. Dutta, S. G. Napholtz, R. T. Yen, R. L. Brown, T. M. Shen, and N. A. Olsson, Electron. Lett. **20**, 727 (1984).
[8]I. P. Kaminow, L. W. Stulz, J. S. Ko, B. I. Miller, R. D. Feldman, J. C. DeWinter, and M. A. Pollack, Electron. Lett. **19**, 878 (1983).
[9]E. A. Rezek, R. Chin, N. Holonyak, Jr., S. W. Kirchoefer, and R. M. Kolbas, J. Electron. Mater. **9**, 1 (1980).
[10]B. W. Hakki and T. L. Paoli, J. Appl. Phys. **46**, 1299 (1975).
[11]W. T. Tsang, C. Weisbuch, R. C. Miller, and R. Dingle Appl. Phys. Lett. **35**, 673 (1979).
[12]H. Kobayashi, H. Iwamura, T. Saku, and K. Otsuka, Electron. Lett. **19**, 167 (1983).
[13]N. A. Olsson, N. K. Dutta, and K.-Y. Liou, Electron. Lett. **20**, 121 (1984); N. K. Dutta, N. A. Olsson, L. A. Koszi, P. Besomi, and R. J. Nelson, J. Appl. Phys. **56**, 2167 (1984).
[14]R. A. Linke (unpublished).
[15]M. G. Burt, Electron. Lett. **20**, 27 (1984).
[16]Y. Arakawa, K. Vahala, and A. Yariv, Appl. Phys. Lett. **45**, 950 (1984).
[17]N. K. Dutta, N. A. Olsson, and W. T. Tsang, Appl. Phys. Lett. **45**, 836 (1984).

Pulse compression in optical fiber filters

Herbert G. Winful
GTE Laboratories Inc., 40 Sylvan Road, Waltham, Massachusetts 02254

(Received 5 December 1984; accepted for publication 21 December 1984)

A method is described for compressing optical pulses at any wavelength in an optical fiber. It uses the negative dispersion property of permanent phase gratings created within the fiber. No external grating pair is required.

Current techniques for pulse compression at optical frequencies rely on methods originally developed in the art of chirp radar.[1] A frequency sweep or chirp is applied to the pulse so that the trailing edge is shifted upward in frequency relative to the leading edge. When such a chirped pulse propagates along a dispersive delay line, the rear of the pulse will travel faster than the front if the sign of the dispersion is negative. As a result, the pulse is compressed in time. For optical pulses propagating along an optical fiber, the frequency chirp is produced by the process of self-phase modulation which results from the instantaneous intensity-dependent refractive index of the fiber material. Compression is then achieved by using an external grating pair or other anomalously dispersive delay line.[2] For wavelengths longer than 1.3 μm, optical fibers exhibit negative dispersion, hence that property has been used to achieve pulse compression at those wavelengths without an external grating.[3]

In this letter, the use of nonlinear distributed filters is suggested for pulse compression. Such filters operate on a principle of dispersive coupling between modes which may be either co-propagating or counterpropagating. When these filters are imbedded in an optical fiber they alter its dispersion characteristics so that pulse compression without an external grating pair becomes possible at wavelengths shorter than 1.3 μm. For definiteness, I analyze the counterpropagating geometry which is the situation that is obtained when a phase grating is created in an optical fiber. The co-propagating geometry is represented, for example, by a nonlinear directional coupler or by the recently demonstrated fiber-polarization-rocking filter.[4]

The basic component of the proposed pulse compression scheme is an optical fiber within which a phase grating has been created. Germania (GeO_2) doped silica fibers have been shown to possess a certain photosensitivity that permits the use of standard holographic techniques to write permanent gratings within the core of the fiber.[5] These gratings function as Bragg reflection filters whose length, in principle, is limited only by the coherence length of the exposing laser. The fiber core after grating formation is characterized by a refractive index variation of the form

$$n = n_0 + n_1 \cos(2\beta_0 z), \tag{1}$$

where $n_1 \ll n_0$, $\beta_0 = 2\pi n_0/\lambda_0$, and λ_0 is the free-space wavelength that satisfies the Bragg condition for the periodic structure. For typical fiber filters n_1 is of order 10^{-5}. The strength of the contradirectional mode coupling induced by the periodic index variation is measured by a coupling constant $\kappa = \pi n_1/\lambda_0$. It is also useful to define a detuning parameter $\Delta\beta$ as the difference between the propagation constant of a guided mode and the wave number of the grating:

$$\Delta\beta(\omega) = \beta - \beta_0 = n_0(\omega)\omega/c - \beta_0. \tag{2}$$

A Bragg filter is a dispersive structure, its properties being highly dependent on the light wavelength. Coupled mode theory[6] yields the amplitude and phase of the filter transmission coefficient as

 0003-6951/85/060527-03$01.00

$$T(\omega)\exp(i\phi(\omega)) = \frac{S\exp(i\beta_0 L)}{S\cosh(SL) - i\Delta\beta(\omega)\sinh(SL)}, \quad (3)$$

where

$$S = (\kappa^2 - \Delta\beta^2)^{1/2} \quad (4)$$

and L is the filter length. The corresponding intensity reflection coefficient is shown in Fig. 1(a) for a filter with normalized coupling constant $\kappa L = 4$. Note that transmission is high outside the stop band and periodically attains a value of unity (zero reflectivity). For pulse compression purposes an important property of the filter is its group velocity dispersion (GVD) which is given by

$$D = -\frac{2\pi c}{L\lambda^2}\frac{d^2\phi}{d\omega^2}. \quad (5)$$

If material dispersion is neglected, the filter dispersion is readily evaluated from Eq. (3). Figure 1(b) shows the dispersion parameter ϕ'' as calculated for a 1-m-long fiber filter with $\kappa = 4\ \mathrm{m}^{-1}$. It is seen that the dispersion due to the filter can be positive or negative depending on the detuning. Furthermore, this dispersion is orders of magnitude larger than the material dispersion which is of order $10^{-25}\ \mathrm{s}^2$ for a 1-m-long silica fiber at visible wavelengths. The enormous values of GVD available in a fiber filter must, of course, be regarded with caution if the dispersion changes rapidly within the frequency range spanned by the bandwidth of an incident pulse.[7]

The presence of group velocity dispersion alone will always lead to the broadening of a transform limited pulse. If the pulse is chirped, however, pulse compression becomes possible whenever the dispersion has the right sign to reverse the chirp. In an optical fiber filter the nonlinear polarization that results in frequency chirping may be written

$$P^{\mathrm{NL}} = n_0\delta n(E)E/2\pi, \quad (6)$$

where δn is the essentially instantaneous index change given by

$$\delta n = 1/2\, n_2|E|^2 \quad (7)$$

and n_2 is the nonlinear index coefficient whose value for silica fibers is 1.1×10^{-13} esu. Note that this index change is distinct from the "photorefractive" effect used in grating formation which depends on the time integrated writing power, responds in minutes, and is permanent once created. Pulse propagation in the nonlinear periodic structure is then described by the following coupled equations for the slowly varying components of the field E[8]:

$$\frac{\partial E_F}{\partial z} + \frac{n_0}{c}\frac{\partial E_F}{\partial t} = i\kappa E_B e^{-i2\Delta\beta z} + i\gamma(|E_F|^2 + 2|E_B|^2)E_F, \quad (8a)$$

$$\frac{\partial E_B}{\partial z} - \frac{n_0}{c}\frac{\partial E_B}{\partial t} = -i\kappa E_F e^{i2\Delta\beta z} - i\gamma(|E_B|^2 + 2|E_F|^2)E_B, \quad (8b)$$

where $\gamma = \pi n_2/\lambda$. The terms on the right-hand side cubic in the fields describe self-phase modulation while the linear terms describe the dispersive coupling between forward (E_F) and backward (E_B) fields. These equations are obtained by using the nonlinear polarization (6) and the spatially periodic refractive index in Maxwell's equations and making use of the slowly varying envelope approximation.

To simulate the behavior of the fiber-filter pulse compressor, Eqs. (8) were integrated numerically along forward and backward characteristics for a variety of input pulses. Figure 2 shows a Gaussian input pulse whose full width at half-maximum is τ (solid curve) and the resulting transmitted compressed pulse. The initial detuning is $\Delta\beta/\kappa = 3$ so that the carrier frequency of the pulse lies in a region of negative filter dispersion and relatively high transmission. Note that the compressed pulse is also enhanced in peak power, i.e., true compression rather than pulse truncation occurs. The actual peak intensity of the input pulse used here is $I/I_c = 2\kappa L$, where $I_c = 2\lambda/3\pi n_2 L$. For these intensity levels the intensity-dependent index change δn is of the order of the spatially periodic index perturbation n_1. For a 1-m-long fiber filter of core diameter 2.5 μm and $\kappa L = 4$ (a readily

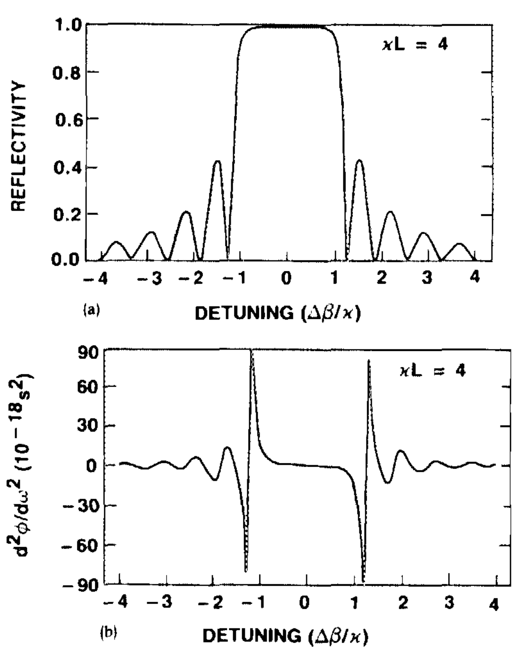

FIG. 1. (a) Reflectivity vs normalized detuning for an optical fiber filter of $\kappa L = 4$. (b) Second derivative of the phase shift vs detuning for the same fiber filter.

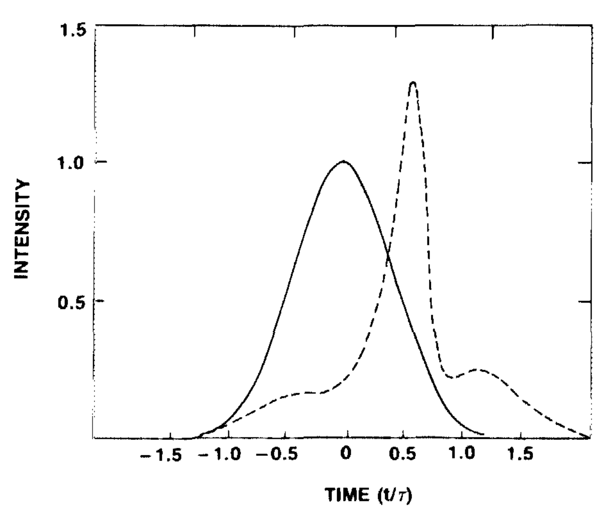

FIG. 2. Incident (solid curve) and transmitted pulse in fiber-filter pulse compression. Here $\kappa L = 4$ and $\tau = 0.1 n_0 L/c$.

attainable value[9]) the input peak power for a factor of three compression is about 100 W. Larger compression ratios can be obtained by optimizing the input intensity, coupling constant, detuning, and input pulse width. It should be noted that in a nonlinear distributed filter, the nonlinearity and dispersion are strongly coupled. The dispersion is intensity dependent, hence the low intensity bandwidth of the filter is not an indication of achievable compressed pulse widths.

There are several features which make this method of pulse compression attractive. It can be used at any wavelength where the photorefractive effect exists. The anomalous dispersion of the phase grating may enable soliton propagation at visible wavelengths. In fact, it has been shown that the presence of a longitudinal inhomogeneity in a fiber may lead to solitons which maintain their shape, but acquire time-dependent velocities and accelerations.[10] The filter itself can be tuned (e.g., by temperature or stress) to vary the dispersion properties at a fixed wavelength. Furthermore, one can create chirped or tapered filters to produce a broadband response and even larger negative dispersion. No external grating pair is required in this method of pulse compression.

This research was partially supported by the National Science Foundation under grant ECS-8312845.

[1] J. R. Klauder, A. C. Price, S. Darlington, and W. J. Albersheim, Bell Syst. Tech. J. **39**, 745 (1960).
[2] E. B. Treacy, IEEE J. Quantum Electron. **QE-5**, 454 (1969); H. Nakatsuka, D. Grischkowsky, and A. C. Balant, Phys. Rev. Lett. **47**, 910 (1981); C. V. Shank, R. L. Fork, R. Yen, R. H. Stolen, and W. J. Tomlinson, Appl. Phys. Lett. **40**, 761 (1982).
[3] L. F. Mollenauer, R. H. Stolen, J. P. Gordon, and W. J. Tomlinson, Opt. Lett. **8**, 289 (1983).
[4] R. H. Stolen, A. Ashkin, W. Pleibel, and J. M. Dziedzic, Opt. Lett. **9**, 300 (1984).
[5] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, Appl. Phys. Lett. **32**, 647 (1978).
[6] H. Kogelnik, Bell Syst. Tech. J. **48**, 2909 (1969).
[7] L. Brillouin, *Wave Propagation and Group Velocity* (Academic, NY, 1960).
[8] H. G. Winful and G. D. Cooperman, Appl. Phys. Lett. **40**, 298 (1982).
[9] J. Bures, J. Lapierre, and D. Pascale, Appl. Phys. Lett. **37**, 860 (1981).
[10] B. Bendow, P. D. Gianino, N. Tzoar, and M. Jain, J. Opt. Soc. Am. **70**, 539 (1980).

Analysis of rib waveguides with sloped rib sides

Nadir Dagli and Clifton G. Fonstad
Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, and Center for Materials Science and Engineering,[a] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(Received 19 November 1984; accepted for publication 7 January 1985)

Using a mode matching technique, an approximate microwave equivalent circuit is developed for a dielectric step discontinuity in the transverse direction of a dielectric waveguide. Using this basic building block, rib waveguides with sloped sides are analyzed by approximating the actual rib profile with a staircase function, and cut-off conditions for E_{12} and E_{21} modes are calculated. The results of the theoretical analysis are verified with experiments performed on homojunction GaAs rib waveguides. Finally, an effective rib width appropriate for applying the results of analyses of ideal structures to sloped sided guides is identified.

For integrated optics in III-V compound semiconductors, rib guides are attractive choices since horizontal and vertical index steps are easily controllable. In addition to index control, however, it is also important to be able to control the mode pattern and propagation constant of the guided mode as accurately as possible as a function of cross-sectional geometry. Several methods exist to analyze rib guides, all of which are approximate[1,2] and deal with an ideal structure with vertical rib sides.

In practice, however, rib guides produced by chemical etching techniques have sloped sides. In the analysis of such structures, an effective width is usually introduced in an ad hoc manner and the structure is analyzed as the ideal structure with this effective width. This makes the results even more approximate and makes such techniques very crude for applications like coupled guides where greater accuracy is desired. Using a waveguide analysis technique developed recently,[3] it is possible to model such structures accurately without assuming effective widths. In this letter this method of analysis is explained and its predictions are verified experimentally.

Recently it has been shown that it is possible to model rib guides using a microwave equivalent circuit based on a mode matching technique.[3] In general, it is possible to represent the uniform layered portions of the structure as uniform transmission line sections, and if only the guided modes of the uniform layered structures are taken into account, the step discontinuities can be modeled as a transformer network. Neglecting TE-TM conversion at the discontinuity, which is very small for the rib guide, a simplified but accurate equivalent circuit is obtained. The transverse step

[a] A National Science Foundation Materials Research Laboratory supported in part through grant No. DMR 81-19295.