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Generation of time-aligned picosecond pulses on wavelength-division-multiplexed beams in a nonlinear fiber

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A fundamentally different way to generate time-aligned data pulses on wavelength-division-multiplexed (WDM) beams in a single-mode fiber is found. A large-amplitude pulse called a shepherd pulse is launched on one of the copropagating beams (shepherd pulse is defined as a pulse that can affect other copropagating pulses in a WDM format while maintaining its own propagation behavior). Initially at the launching plane no other pulse exists on any of the other copropagating wavelength-division-multiplexed beams. Due to the nonlinear cross-phase modulation effect, time-aligned pulses are generated on all other beams after a given fiber length. Both theoretical and experimental results are presented. [S1063-651X(98)09105-3]

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I. INTRODUCTION

The difficulty in the generation of time-aligned pulses in the picosecond range on wavelength-division-multiplexed (WDM) beams is well recognized. Yet, these time-aligned pulses are the backbone for the future ultra-high-speed bit-parallel communication system [1,2]. A way to generate these pulses is described here.

In spite of the intrinsically small value of the nonlinearity coefficient in fused silica, due to low loss and long interaction length, the nonlinear effects in optical fibers made with fused silica cannot be ignored even at relatively low power levels [3]. This nonlinear phenomenon in fibers has been used successfully to generate optical solitons [4], to compress optical pulses [5], to transfer energy from a pump wave to a Stokes wave through the Raman gain effect [6], to transfer energy from a pump wave to a counterpropagating Stokes wave through the Brillouin gain effect [7], to produce four-wave mixing [8], to dynamically shepherd pulses [9], and to enhance pulse compression [10]. Now, we wish to add one more: the generation of time-aligned pulses.

In a wavelength-division-multiplexed fiber system, the cross-phase modulation (CPM) effects [11,12] caused by the nonlinearity of the optical fiber are unavoidable. These CPM effects occur when two or more optical beams copropagate simultaneously and affect each other through the intensity dependence of the refractive index. This CPM phenomenon is used to generate time-aligned data pulses.

II. THEORETICAL FOUNDATION

The fundamental equations governing M numbers of copropagating waves in a nonlinear fiber including the CPM phenomenon are the coupled nonlinear Schrödinger equations [9–11]:

$$i\frac{\partial u_j}{\partial \xi}=\frac{\mathrm{sgn}(\beta_{2j})L_{D1}}{2L_{Dj}}\frac{\partial^2 u_j}{\partial \tau^2}-i\frac{d_{1j}}{T_0}L_{D1}\frac{\partial u_j}{\partial \tau}-\frac{L_{D1}}{L_{NLj}}\left[\exp(-\alpha_j L_{D1}\xi)|u_j|^2+2\sum_{m\neq j}^{M}\exp(-\alpha_m L_{D1}\xi)|u_m|^2\right]u_j \qquad (j=1,2,3,\ldots,M). \tag{1}$$

Here, for the jth wave, u_j is the normalized slowly varying amplitude of the wave, β_{2j} the dispersion coefficient ($\beta_{2j}=dv_{gj}^{-1}/d\omega$), v_{gj} the group velocity, α_j the absorption coefficient, γ_j the nonlinear index coefficient, $d_{1j}=(v_{g1}-v_{gj})/v_{g1}v_{gj}$, $L_{NLj}=1/(\gamma_j P_{0j})$, $L_{Dj}=T_0^2/|\beta_{2j}|$, $\tau=[t-(z/v_{g1})]/T_0$, and $\xi=z/L_{D1}$, where z is the direction of propagation along the fiber and t is the time coordinate. Also, T_0 is the pulse width, P_{0j} is the incident optical power of the jth beam, and d_{1j}, the walk-off parameter between beam 1 and beam j, describes how fast a given pulse in beam j passes through the pulse in beam 1. In other words, the walk-off length is $L_{W(1j)}=T_0/|d_{1j}|$. So, $L_{W(1j)}$ is the distance for which the faster moving pulse (say, in beam j) completely walked through the slower moving pulse in beam 1. The nonlinear interaction between these two optical pulses ceases to occur after a distance $L_{W(1j)}$. For cross-phase modulation to take effect significantly, the group-velocity mismatch must be held to near zero.

It is also noted from Eq. (1) that the summation term in the bracket representing the cross-phase modulation effect is twice as effective as the self-phase modulation effect for the same intensity. This means that the nonlinear effect of the fiber medium on a beam may be enhanced by the copropagation of another beam with the same group velocity.

Equation (1) is a set of simultaneous coupled nonlinear Schrödinger equations that may be solved numerically by the

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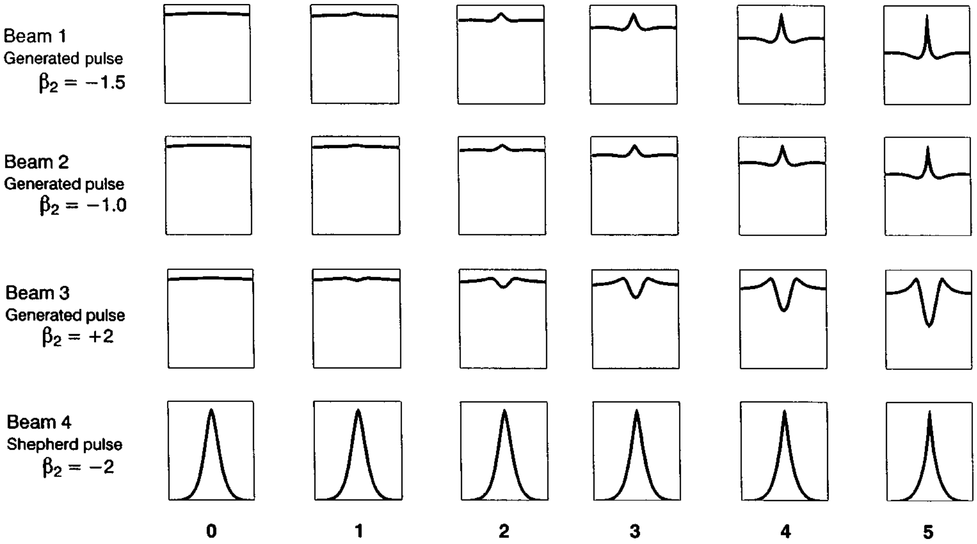

FIG. 1. Pulse evolution picture for the generation of three simultaneous pulses on three beams with separate wavelengths by a large-amplitude shepherd pulse on the fourth beam. For beam 1, $\beta_2 = -1.5$, for beam 2, $\beta_2 = -1.0$, for beam 3, $\beta_2 = +2.0$, and for beam 4, the shepherd pulse beam, $\beta_2 = -2.0$. The effect of different values of the dispersion coefficient on the induced pulses can be seen. In the negative β_2 region (the anomalous group-velocity dispersion region of the fiber), the induced pulses are ''bright'' pulses, and in the positive β_2 region (the normal group-velocity dispersion region of the fiber) the induced pulse is a ''dark'' pulse. The higher the $|\beta_2|$ value, the higher the amplitude of the induced pulse. (This case does not correspond to the case considered in Figs. 3, 4, and 5.)

split-step Fourier method, which was used successfully earlier to solve the problem of beam propagation in complex fiber structures, such as the fiber couplers [13], and to solve the thermal blooming problem for high-energy laser beams [14]. According to this method, first, the solutions may be advanced using only the nonlinear part of the equations. Then the solutions are allowed to advance using only the linear part of Eq. (1). This forward stepping process is repeated over and over again until the desired destination is reached. The Fourier transform is accomplished numerically via the well-known fast-Fourier-transform technique.

III. HOW TO GENERATE TIME-ALIGNED PULSES

A high-power, picosecond pulse, called the shepherd pulse, is launched on a given beam. A number of low-power beams that are selected based on the wavelength-division-multiplexed format are launched without any signal pulses into a single-mode nonlinear fiber. These beams copropagate with the beam carrying the shepherd pulse in this fiber. It will be shown, first through numerical simulation results, and then through experimental measurements, that time-aligned pulses will appear on these low-power WDM beams. The nonlinear cross-phase modulation effect in a single-mode fiber is instrumental in the generation of these time-aligned pulses. It is also required that the ''walk-off'' among all the beams be kept at a minimum acceptable value. A more detailed discussion on this requirement will be given later.

IV. COMPUTER SIMULATION RESULTS

Computer-simulation results for the generation of three simultaneous pulses on three beams with separate wavelengths by a large amplitude shepherd pulse on the fourth beam are shown in Fig. 1. It is assumed that wavelength separation among the beams is larger than 5 nm and the shepherd pulse has a pulse width of 60 ps. Due to this wide wavelength separation of the beams as well as the width of the shepherd pulse, the four-wave-mixing effect is negligible for this case. Other parameters are: the length of fiber $L = 20$ km, the dispersion coefficient $|\beta_2| = 2\ \mathrm{ps}^2/\mathrm{km}$, the operating wavelength of beam 1 $\lambda_1 = 1.55\ \mu\mathrm{m}$, the operating wavelength of beam 2 $\lambda_2 = 1.545\ \mu\mathrm{m}$, the operating wavelength of beam 3 $\lambda_3 = 1.535\ \mu\mathrm{m}$, the operating wavelength of beam 4 $\lambda_4 = 1.555\ \mu\mathrm{m}$, the nonlinear index coefficient $\gamma = 20\ \mathrm{W}^{-1}\mathrm{km}^{-1}$, the attenuation or absorption of each beam in fiber $\alpha = 0.2$ dB/km, the group velocity of the beam $v_g = 2.051\,147 \times 10^8$ m/sec, the walk-off parameter between the slowest beam and the fastest beam $d_{12} < 3$ ps/km, and the pulse width $T_0 = 60$ ps. It has been assumed that the dispersion coefficients for these beams are: for beam 1, $\beta_2 = -1.5$, for beam 2, $\beta_2 = -1.0$, for beam 3, $\beta_2 = +2.0$, and for beam 4, the shepherd pulse beam, $\beta_2 = -2.0$ The effect of different values of the dispersion coefficient on the induced pulses can be seen from the resultant data. In the negative β_2 region (the anomalous group-velocity dispersion region), the induced pulses are ''bright'' pulses and, in the positive β_2 region (the normal group-velocity dispersion region), the induced pulse is a ''dark'' pulse, i.e., a dip. The higher the $|\beta_2|$ value, the higher the amplitude of the induced pulse. For shepherd pulse having a large amplitude, say, $N_S = 5$, where N_S is the soliton number for the shepherd pulse, the fiber length at which the shepherd pulse experiences maximum pulse compression is $0.105 L_{DS}$ where L_{DS} is the dispersion length for the shepherd pulse. This is also the length at which maximum amplitude for the induced pulse is generated. The evolution of these generated pulses from 0 to this length is shown in Fig. 1.

Our simulation shows that large walk-off among the beams, i.e., walk-off larger than a full shepherd pulse width within the dispersion length for the shepherd pulse, would

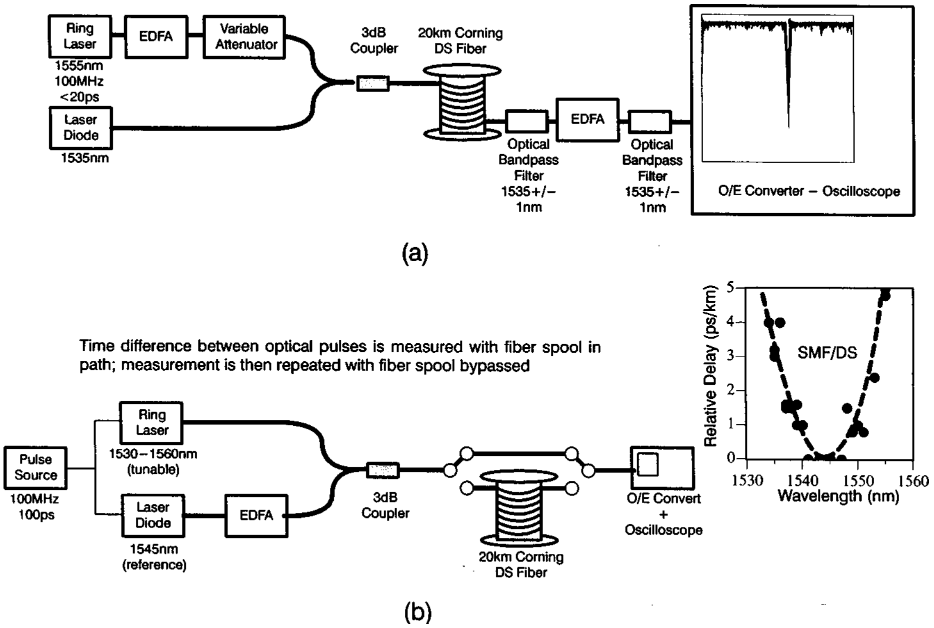

FIG. 2. (a) A schematic block diagram for the experimental setup to measure the generated pulses. (b) A schematic block diagram for the experimental setup to measure the ''walk-off'' characteristics of the Corning DS fiber. The maximum walk-off for the wavelength range 1535–1560 nm is less than 4 ps/km.

destroy the capability of the shepherd pulse to generate time-aligned pulses on the copropagating primary beams. It is for this reason that the selection of a proper fiber is of utmost importance. The following experiment will show that this demand, although rather stringent, can still be satisfied.

V. EXPERIMENTAL SETUP AND RESULTS

Schematic block diagrams of two experimental setups are shown in Fig. 2. The pulse source is a tunable erbium-doped fiber-ring laser, producing a 100-MHz train of pulses 60 ps in width between the wavelength range of 1530–1560 nm. This erbium ring pulse is named the shepherd pulse, operating at a peak power of higher than 200 mW. The primary sources are distribution feedback laser diodes at 1535, 1540, 1545, and 1557 nm, operated under a dc bias well above threshold. This cw output from the primary laser diode source is about 1 mW, which is amplified through an erbium-doped fiber amplifier to around 33 mW.

A. Measurement of fiber characteristics

As indicated in Sec. IV, the selection of a proper fiber is of great importance in the successful generation of time-aligned pulses on copropagating WDM beams. The Corning dispersion shifted (DS) fiber [15] is chosen to be the single-mode fiber for the experiment because of its desirable dispersion and walk-off characteristics. To learn quantitatively the behavior of this fiber, the walk-off characteristics of this fiber are measured and displayed in Fig. 3. It is seen that for the wavelength range of interest (1535–1560 nm), the dispersion coefficient β_2 varies between $+2$ and -2 ps^2/km. The difference of group velocities as a function of the wavelength of the beams varies between 0 and 4 ps/km. An erbium-doped fiber amplifier (EDFA) is used to boost the power at the receiver.

B. Generation of time-aligned pulses on copropagating WDM beams

Two sets of experiments were performed: The first set dealt with the generation of ''dark'' pulses on two or three semiconductor laser sources by a shepherd pulse on the ring laser; the second set dealt with the generation of ''bright'' pulses on a semiconductor laser source by a shepherd pulse on the ring laser. Signals from these sources (one or more signal sources from semiconductor lasers and one shepherd source from a ring laser) of different wavelengths are combined using two 2-to-1 fiber couplers. The combined output is sent through a 20-km spool of Corning DS fiber. At the output end of the fiber, an optical bandpass filter is used to reject the shepherd pulse signal from the ring laser. The signal from each laser diode is detected and viewed on an oscilloscope. A picture of this output is shown in Fig. 2(a). A dip (dark pulse) or a rise (bright pulse) on the cw signal from a laser diode indicates the presence of a generated pulse as predicted by the computer-simulation result.

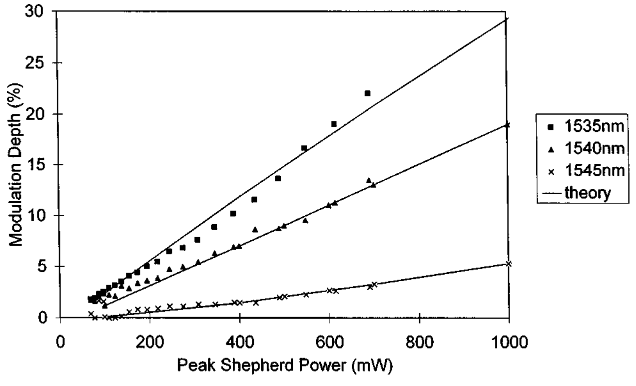

FIG. 3. Measured and computed modulation depths of the generated ''dark'' pulses on three different wavelength beams as a function of the shepherd-pulse peak power.

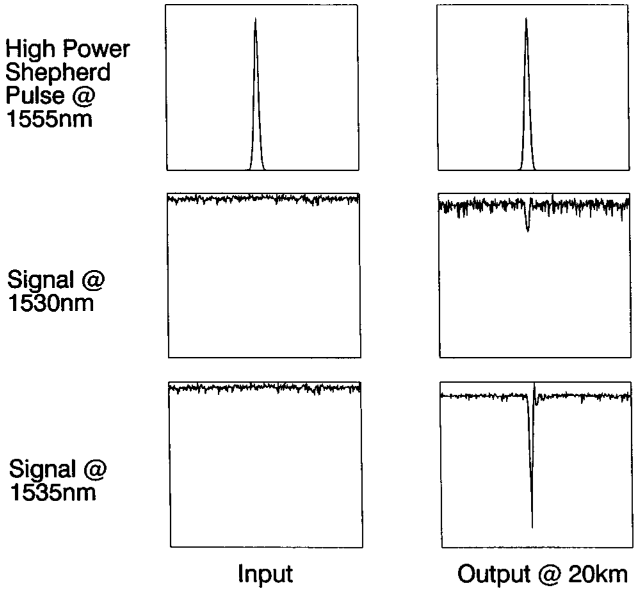

FIG. 4. Oscilloscope picture for the generated pulses on two different wavelength primary beams by a copropagating shepherd pulse on the third beam. ''Dark'' pulses are generated on the diode laser beams, since the operating wavelengths of these primary beams fall into the normal group-velocity dispersion region of the fiber.

1. Set 1: Generation of ''dark'' pulses

Systematic measurements are made for pulses generated on two or three primary cw beams from laser-diode sources due to the presence of a shepherd pulse on a beam from the ring laser. Figure 4 shows the input and output pulses on the two primary cw beams with wavelengths 1530 and 1535 nm, and on the ring laser beam operating at 1555 nm. It is seen that there were no pulses on the two primary beams at the input and there was a large shepherd pulse on the ring laser beam at the input. After passing through the fiber, there appeared three time-aligned copropagating output pulses on all three beams. As predicted by the theory, two dark pulses were generated on the primary diode laser beams because the operating wavelengths fell in the normal group-velocity dispersion region of the fiber and one was the shepherd pulse on the ring laser beam.

Shown in Fig. 3 is a plot of modulation depths on the cw beams as a function of the shepherd pulse peak power. Solid lines represent the computer-simulation results and the data points represent the measured results. Very close agreement is observed. It is noted that walk-off between the shepherd pulse and the generated primary pulses is less than 1 ps/km. For a fiber length of 20 km, the maximum pulse misalignment is 20 ps or 1/3 pulse width without the pulse-shepherding effect. It is expected that the presence of the unavoidable pulse-shepherding effect will diminish the pulse misalignment to a negligible level, as observed in the experimental results.

2. Set 2: Generation of ''bright'' pulses

To verify the theoretical prediction that bright pulses can be generated if the operating wavelength of the primary laser diode falls in the anomalous group-velocity dispersion region of the fiber, the following experiment was performed: Two beams, one from the ring laser, carrying the shepherd pulse at 1535 nm, and the other from the diode laser, carrying no pulse at 1557 nm, were combined and sent through the Corning DS fiber. The input and output pulses on these beams are displayed in Fig. 5. As predicted by the theory, a bright pulse is generated on the diode laser beam because its operating wavelength falls in the anomalous group-velocity dispersion region of the fiber.

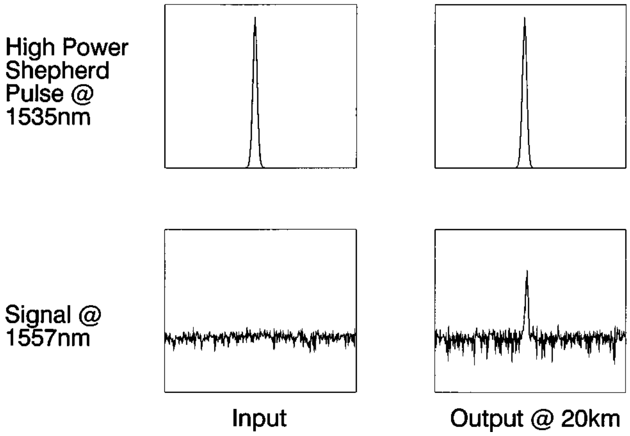

FIG. 5. Oscilloscope picture for the generated pulse on a primary beam by a copropagating shepherd pulse on the second beam. The ''bright'' pulse is generated on the diode laser beam, since the operating wavelength of the primary beam falls into the anomalous group-velocity dispersion region of the fiber.

VI. CONCLUSIONS

The above experiments show that through the use of a shepherd pulse on a copropagating wavelength-division-multiplexed beam, a simple way is found to generate time-aligned pulses on the other different wavelength beams in a nonlinear fiber. This was accomplished experimentally using a Corning single-mode-fiber–dispersion-shifted fiber. It should be noted that the success of this technique depends on the condition that the amount of walk-off or drifting between the large-amplitude shepherd pulse and the generated pulses must be less than half of the pulse width of the shepherd pulse for the entire pulse-generation interaction length of fiber. It should be noted that these generated pulses are ''stable'' pulses in the sense that they remain even after the shepherd pulse is channeled away. Successful generation of these time-aligned pulses on WDM beams is crucial to the realization of the future ultrahigh data-rate bit-parallel wavelength-division-multiplexed single-fiber transmission system.

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