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Experimental Verification of the Pulse Shepherding
Concept in Dispersion-Shifted Single-Mode Fiber
for Bit-Parallel Wavelength Links

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ABSTRACT

A new way to dynamically control in-flight pulses in a wavelength division multiplexed (WDM) single-mode fiber system was proposed at the MPPOI '96 Conference. That system functionally resembles an optical fiber ribbon cable, except that all the bits pass on one fiber optic waveguide. This single fiber bit parallel wavelength link can be used to extend the (speed x distance) product of emerging cluster computer networks, such as, the MyriNet, SCI, Hippi-6400, ShuffleNet, etc. Here, we shall present the first experimental evidence that this pulse shepherding effect can be observed in a commercially available Corning DS (dispersion-shifted) fiber. Computer simulation results will first be presented for the case observed in the laboratory setup. A discussion of the experiment setup and measurement procedures will be given. Experimental results will then be compared with computer generated results. Excellent agreement is observed. Future experiments dealing with the shepherding effect among more than two co-propagating pulses will be performed.

I. Introduction

The concept of using a shepherd pulse to promote time-alignment of co-propagating pulses in a bit-parallel wavelength division multiplexed system [1] for a single-mode fiber was presented at the MPOI '96 Conference [2]. The proposed concept is based on the cross phase modulation (CPM) effects [3] caused by the nonlinearity of the optical fiber in a wavelength division multiplexed (WDM) system. These CPM effects occur when two or more optical beams co-propagate simultaneously and affect each other through the intensity dependence of the refractive index. This CPM phenomenon can be used to produce an interesting pulse shepherding effect to align the arrival time of pulses which are otherwise misaligned. This same CPM effect can also be used to generate time-aligned co-propagating pulses on different wavelength beams.

An example of the pulse shepherding effect [4] is shown below:

Let us assume that two gaussian pulses on two different wavelength beams with wavelengths of $1.55 \mu\text{m}$ and $1.546 \mu\text{m}$, originating in an aligned position as shown in Fig. 1(a), begin to separate from each other due to slight difference in the group velocities for these two beams. Without the presence of a shepherd pulse, these beams will be approximately $1/2$ pulsewidth apart at 50 km downstream as can be seen from Fig. 1(a). With the shepherd pulse of $2 \exp(-0.5 \tau^2)$ on a third beam with wavelength $1.542 \mu\text{m}$, originally aligned with the two shepherded pulses and propagating at the same velocity as the pulse on beam #1, at 50 km downstream, the shepherded pulses are still aligned as shown in Fig. 1(b).

What this means is that through the introduction of a shepherd pulse on a separate wavelength beam, it is possible to dynamically manipulate, control and reshape pulses on co-propagating beams in a WDM system. This dynamic control feature from a shepherd pulse will enable the eventual construction of a time-aligned bit-parallel wavelength link as an interconnect with exceptionally high speed, low latency, simplified electronics interface (with no speed bottleneck), and extensibility to all-optical packet networks.

Here, we shall present the first experimental result showing the existence of this pulse shepherding effect.

A review of the theoretical background will first be given. Computer simulation results for the case corresponding to that observed in the laboratory will be

presented. Experimental setup and measurement procedures will then be discussed. Measured results will be compared with computer results. Evidence of the shepherding effect will be presented. Finally, a discussion on future experiments dealing with the shepherding effect among more than two co-propagating pulses will be given.

II. A Review of the Theoretical Foundation

The fundamental equations governing M numbers of co-propagating waves in a nonlinear fiber including the CPM phenomenon are the coupled nonlinear Schrodinger equations [3,4]:

$$\begin{aligned} \frac{\partial A_j}{\partial z} + \frac{1}{v_{gj}} \frac{\partial A_j}{\partial t} + \frac{1}{2} \alpha_j A_j \cdot \frac{1}{2} \beta_{2j} \frac{\partial^2 A_j}{\partial t^2} \\ - \gamma_j (|A_j|^2 + 2 \sum_{m \neq j}^M |A_m|^2) A_j \end{aligned} \quad (j = 1, 2, 3, \dots, M) \quad (1)$$

Here, for the jth wave, $A_j(z, t)$ is the slowly-varying amplitude of the wave, v_{gj} , the group velocity, β_{2j} , the dispersion coefficient ($\beta_{2j} = dv_{gj}^{-1}/d\omega$), α_j , the absorption coefficient, and

$$\gamma_j = \frac{n_2 \omega_j}{c A_{eff}} \quad (2)$$

is the nonlinear index coefficient with A_{eff} as the effective core area and $n_2 = 3.2 \times 10^{-16} \text{ cm}^2/\text{W}$ for silica fibers, ω_j is the carrier frequency of the jth wave, c is the speed of light, and z is the direction of propagation along the fiber.

Introducing the normalizing coefficients

$$\tau = \frac{t - (z/v_{g1})}{T(I)}$$

$$d_{1j} = (v_{g1} - v_{gj}) / v_{g1} v_{gj},$$

$$\xi = z / L_{D1},$$

$$L_{D1} = T_0^2 / |\beta_{21}|,$$

and setting

$$u_j(\tau, \xi) = (A_j(z, t) / \sqrt{P_{0j}}) \exp(\alpha_j L_{D1} \xi / 2) \quad (4)$$

$$L_{NLj} = 1 / (\gamma_j P_{0j})$$

$$L_{Dj} = T_0^2 / |\beta_{2j}| \quad (5)$$

gives

$$i \frac{\partial u_j}{\partial \xi} = \frac{\text{sgn}(\beta_{2j}) L_{D1}}{2 L_{Dj}} \frac{\partial^2 u_j}{\partial \tau^2} - i \frac{d_{1j}}{T_0} L_{D1} \frac{\partial u_j}{\partial \tau}$$

$$- \frac{L_{D1}}{L_{NLj}} \left[\exp(-\alpha_j L_{D1} \xi) |u_j|^2 + 2 \sum_{m \neq j}^M \exp(-\alpha_m L_{D1} \xi) |u_m|^2 \right] u_j$$

$$(j = 1, 2, 3, \dots, M) \quad (6)$$

Here, T_0 is the pulse width, P_{0j} is the incident optical power of the j th 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

$$L_{W(1j)} = T_0 / |d_{1j}|. \quad (7)$$

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 (CPM) to take effect significantly, the group-velocity mismatch must be held to near zero.

It is also noted from Eq. (6) that the summation term in the bracket representing the cross-phase modulation (CPM) effect is twice as effective as the self phase modulation (SPM) effect for the same intensity. This means that the nonlinear effect of the fiber medium on a beam may be enhanced by the co-propagation of another beam with the same group velocity.

Equation (6) is a set of simultaneous coupled nonlinear Schrodinger equations which may be solved numerically by the 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 [5], and to solve the thermal blooming problem for high energy laser beams [6]. According to this method, the solutions may be advanced first using only the nonlinear part of the equations. And then the solutions are allowed to advance using only the linear part of Eq. (6). 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. Computer Simulation Results

Based on the above numerical technique, computer simulation is carried out for the case corresponding to that performed in the laboratory.

Two beams with wavelength separated by 5 nm (nanometer) are launched into a single mode fiber: One beam carries a 20 ps gaussian pulse while the other beam carries a 200 ps gaussian pulse to simulate the cw signal in the experiment. The evolution of the two pulses on these two co-propagating beams is the focus of our simulation. It is noted that the four wave mixing effect is negligible for this case. Let us label the initial 20 ps gaussian pulse carried by one of the beam as the shepherd (S) pulse and the other 200 ps pulse on the other beam as the primary (P) pulse. The parameters that we use for the simulation are:

L = length of fiber = 20 km
 β_2 = dispersion coefficient = 2 ps²/km
 λ_1 = operating wavelength of beam #1 = 1.55 μm
 λ_2 = operating wavelength of beam #2 = 1.545 μm
 γ = nonlinear index coefficient = 20 W⁻¹km⁻¹
 α = attenuation or absorption of each beam in fiber
 = 0.2 dB/km
 v_g = group velocity of the beam = 2.051147 x 10⁸ m/sec
 d_{12} = walk-off parameter between beam #1 and beam #2
 < 1 ps/km
 T_0 = pulse width = 20 ps.

Shown in Fig. 2 is the evolution of these two pulses on two different wavelength beams as they propagate in this single mode fiber. Since both pulses are operating in the positive dispersion region, i.e., the dispersion coefficient β_2 is positive, neither pulse will under-go pulse-compression. Since the dispersion coefficient is quite small, for the distance considered, neither pulse will experience significant pulse-broadening.

One notes that in the absence of the shepherding effect (i.e., the CPM effect) these pulses will propagate independent of each other. However, due to the presence of the shepherding effect, very significant changes are observed on the 200 ps primary pulse. On that primary pulse, a dip appears at the location which is aligned with the 20 ps shepherd pulse. This dip appears to grow deeper and broader as both pulses propagate down the fiber, eventually reaching the shape of an inverted 20 ps gaussian pulse. This inverted gaussian pulse is superposed over the 200 ps primary pulse.

This inverted gaussian pulse on a long plateau looks very much like a dark soliton pulse. Also noted is a narrow rim around this dip. Due to the averaging technique used in the experimental measurement, this narrow rim will not appear in the measured picture of the induced primary pulse; only a dip will appear in the picture.

The effect of the small walk-off is to shift the induced inverted pulse on the 200 ps primary beam slightly. The shepherding effect also askews slightly the symmetry of both the shepherd pulse and the induced inverted pulse on the primary pulse.

This very distinctive feature of an induced inverted pulse on a broad primary pulse which is clearly caused by the shepherding effect has been used to experimentally verify the existence of the shepherding effect.

IV. Experimental Setup and Procedures

A schematic block diagram of the experimental setup is shown in Fig. 3. The pulse source is an Erbium Doped Fiber Ring Laser (EDFRL), producing a 100 MHz train of pulses 20 ps in length at a wavelength near 1551 nm. This Erbium Ring pulse is named the shepherd pulse, operating at peak power of higher than 200 mw. The primary source is a DFB laser diode at 1545 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 (EDFA) to around 33 mW.

As shown in Fig. 3, signals from these two sources of two different wavelengths are then combined using a 2 to 1 fiber coupler. 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 pulse signal from the ring laser. The signal from the laser diode is detected and viewed on an oscilloscope. A picture of this output is shown in Fig. 4. A dip on the cw signal is observed indicating the presence of the shepherding effect as predicted by the computer simulation result.

This is the very first time that this shepherding effect has been observed. This experiment also shows that for the length of fiber that we used, i.e., 2 km long, the walk-off effect of this commercially available Corning DS fiber [7] is less than 1 ps/km.

V. Discussion and Future Research

The pictures shown in Fig. 4 clearly demonstrate not only the existence of an induced inverted pulse which can only come about because of the shepherding effect but also the growth of this induced pulse as the interaction distance grows longer as predicted by our computer simulation.

That this shepherding effect is observable in a commercially available Corning SMF-DS fiber [7] (a dispersion shifted fiber) is worth noting. This means we are now in a position to perform further experiments corresponding to the cases produced by computer simulations without waiting for the production of an idealized fiber.

From a practical point of view, it is worth noting that this single fiber bit parallel wavelength link with shepherding pulse(s) can be used to extend greatly the (speed x distance) product of emerging cluster computer networks, such as, the MyriNet, SCI, Hippi-6400, ShuffleNet, etc. The distance may exceed many kilometers, a distance much beyond the capability of fiber ribbons.

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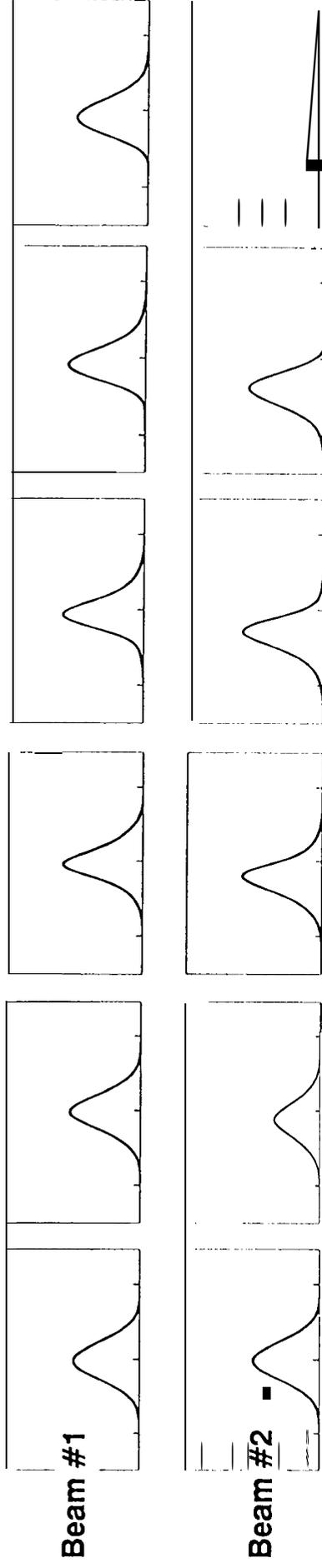
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Figure Captions

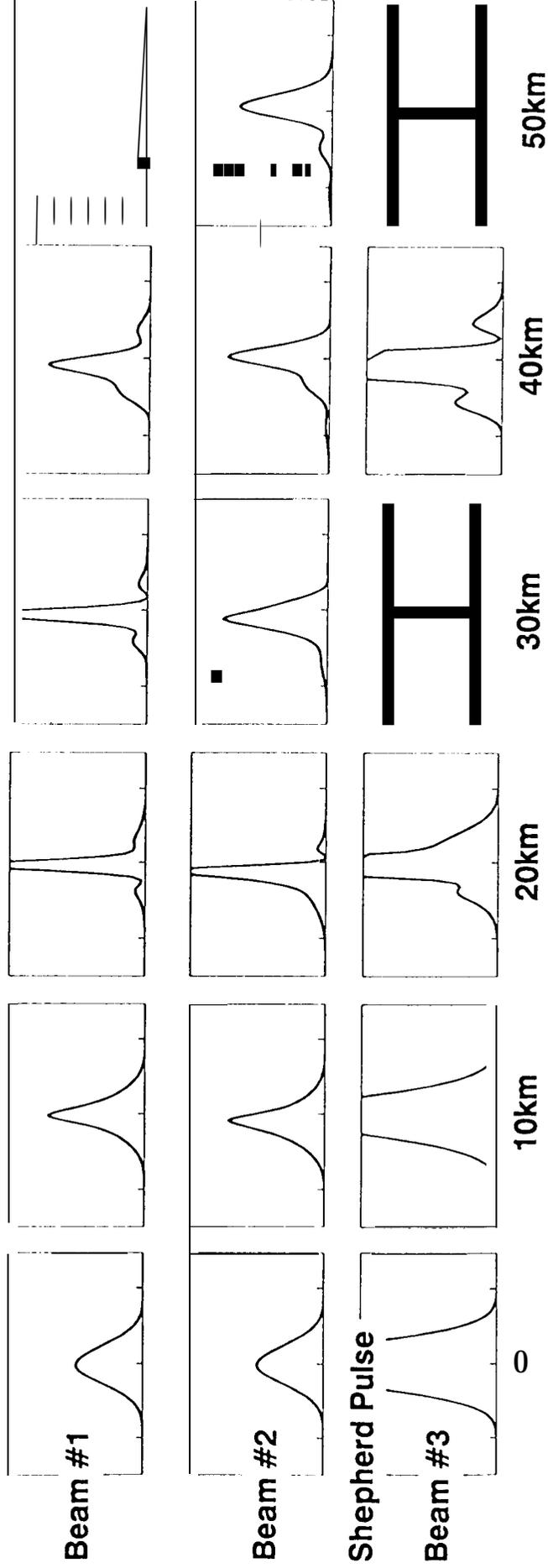
- Figure 1. Evolution of two initially aligned gaussian pulses on two WDM beams, (a) After propagation, separation occurs for pulses on beam #1 and beam #2 without shepherd pulse on the third beam. (b) Alignment maintained for pulses on beam #1-and beam #2 with shepherd pulse on the third beam.
- Figure 2. Computer simulation results for the case of a 20 ps pulse (the shepherd pulse) co-propagating with a 200 ps pulse (approximating a cw primary pulse) in a 20 km dispersion shifted fiber with negligible walkoff. A dip on the 200 ps pulse appeared at the end of the fiber indicating the presence of the shepherding effect.
- Figure 3. Block diagram of the experimental setup to detect the shepherding effect.
- Figure 4. Picture of the output of the cw primary source.
The first line represents the output of the cw primary source signal without the presence of the shepherd pulse. The second line represents the output of the primary pulse with the presence of the shepherd pulse for a 2 km long Corning DS fiber. The third line represents the output of the primary pulse with the presence of the shepherd pulse for a 20 km long Corning DS fiber. A dip is seen indicating the successful interaction of the shepherd pulse with the primary signal.

**Initially Aligned Gaussian Pulses on Dual WDM Beams
Mis-alignment by 1/2 Pulse Width After Propagation**



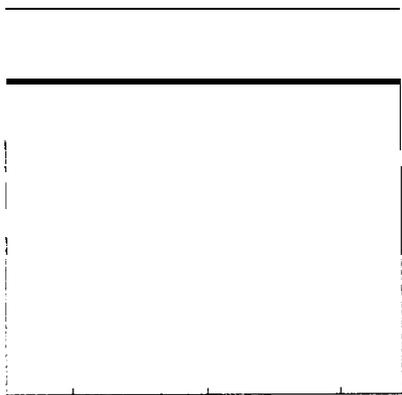
(a) Without Shepherd Pulse

**Alignment Maintained With The Presence of a
Shepherd Pulse on Beam #3**

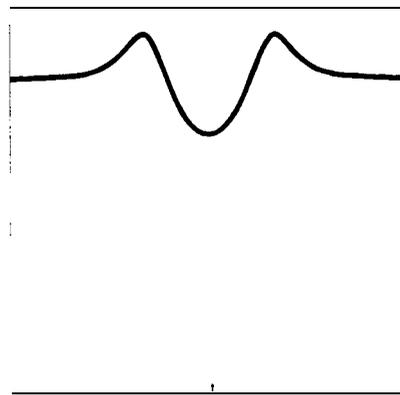


(b) With Shepherd Pulse

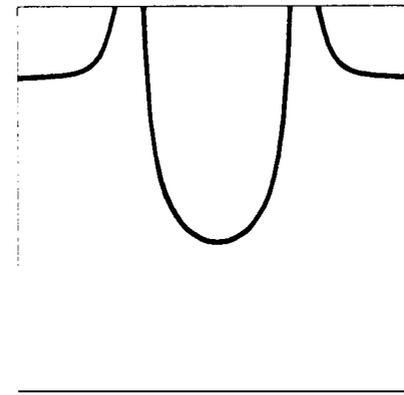
**Primary
Pulse
on Beam 1**



Input

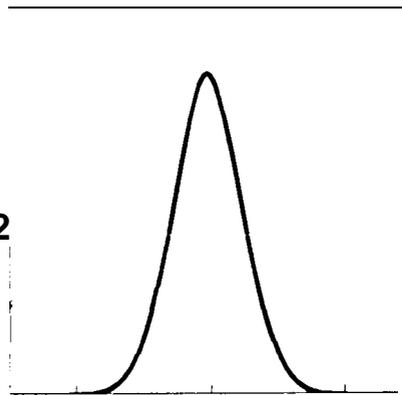


At 2 km



At 20 km

**Shepherd
Pulse
or Beam 2**



Input

Induced pulse on Beam 1 is caused by the presence of the Shepherd pulse on Beam 2.

Fig. 2

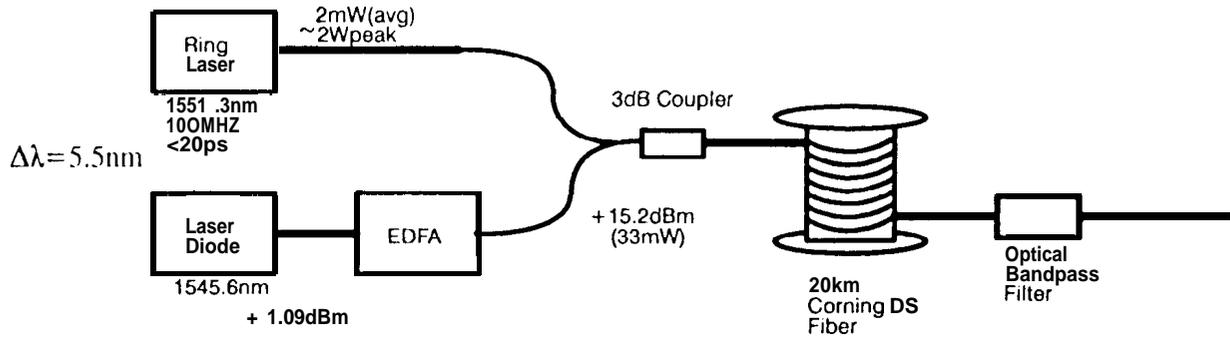


Figure 3

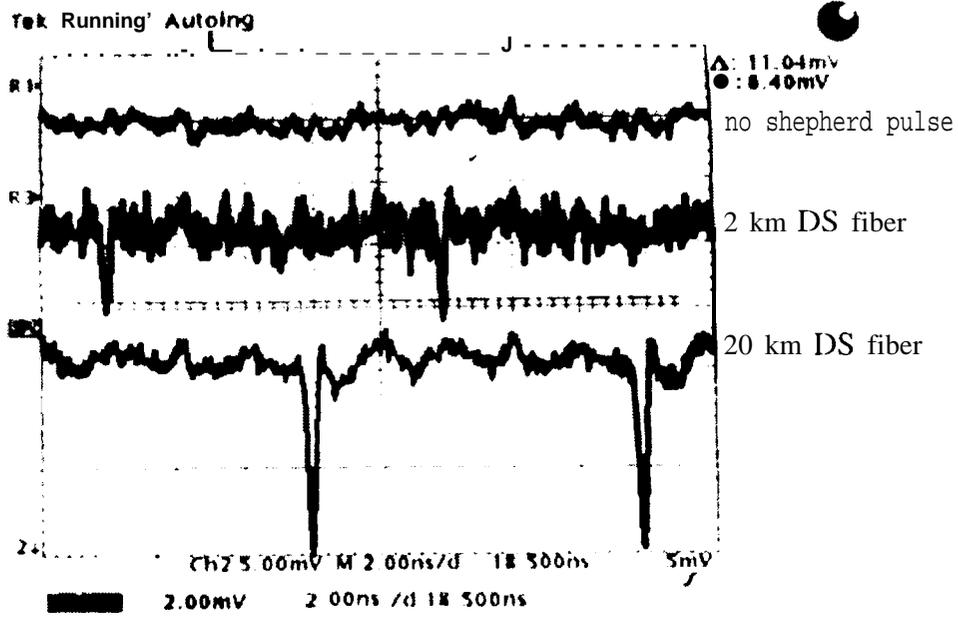


Figure 4