Microbend optical fiber tapped delay line for gigahertz signal processing

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A single-mode optical fiber tapped delay line which utilizes microbend taps has been constructed. The taps are obtained simply and repeatably and are uniform to ± 1 dB. A device with 19 taps and a 1-ns delay between taps was constructed. The average tap strength was 1.5%. The frequency response for the device has been measured and simple programmability has also been demonstrated. Extension of the procedure to devices with 10^2–10^3 taps and 100-ps time delays is possible.

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Tapped delay lines are important in a variety of signal processing applications. They have been used as bandpass filters, matched filters, and other transversal filters. Most tapped delay lines have been implemented using surface acoustic waves[1] and charge-coupled devices.[2] These implementations, however, are limited in performance when bandwidths exceeding 500 MHz are required. Optical fiber tapped delay lines, on the other hand, have low loss and low dispersion which allow much larger time bandwidth products than have been achieved with other technologies. An optical fiber tapped delay line has been implemented using a bundle of 15 multimode fibers cut to different lengths.[3] Recently, a recirculating delay line using single-mode fiber and directional couplers has been demonstrated as a transversal filter.[4,5]

In this letter we report on a tapped delay line which utilizes microbend taps in a single-mode fiber. Uniform taps from the propagating signal have been made simply and repeatably. The device described here has 19 taps with a spacing of 20 cm which corresponds to a 1-ns delay. The design can be extended to make devices with large numbers of taps and much shorter tap spacings.

The taps are obtained by forming short bends in the fiber. A bend causes some of the light from the fiber core to be radiated and some of the light to be coupled into cladding modes. The cladding modes are removed by index matching epoxy before the light travels to the next tap. The radiated light is very directional, and it has an angular divergence which is dependent on the radius of the bend and the angle through which the fiber is bent.

The device described in this letter uses single-mode fiber because it eliminates the dependence of the tap strength on the input mode excitation. Also, single-mode fiber offers a greater time-bandwidth product than multimode fiber.

Light transmitted through optical fiber exhibits phase variations induced by pressure and temperature changes. If a coherent optical carrier is used with a fiber delay line, the positions of the taps must remain constant to less than an optical wavelength, otherwise the relative phase of the tap weighting changes due to environmental fluctuations. In the device discussed here, the coherence length of the source is short compared to the tap spacing. Thus, light intensities, not amplitudes, are added at the detector, and phase variations due to temperature or pressure changes have a negligible effect.

A schematic diagram of the optical fiber tapped delay line is shown in Fig. 1. The source is a General Optronics Model GO-ANA laser diode operating at a wavelength of 0.82 μm. The laser diode has a coherence length on the order of 0.5 mm,[6] and it can be amplitude modulated at frequencies up to 1600 MHz. The tapping pin is suspended by spring-loaded slots and rests against two micrometers. The micrometers can be adjusted to cant the tapping pin which increases the fiber tension for later taps and compensates for the delay line and tap attenuation. A fiber with a transparent acetate jacket is used, and the taps are immersed in an index matching fluid without removing the jacket. The tangentially radiated light is focused by a lens onto a Si *PIN* detector.

A photograph of the radiated light and a scan of the tap uniformity are shown in Fig. 2 for a 19 tap delay line with a 1 ns (20 cm) tap spacing. The device is wound with Corning step index single-mode fiber (11 μm core) with a tension of 27 g. The tapping pin has a radius of 0.15 cm and the wrapping cylinder is 3.175 cm in radius. The tapping pin extends 0.1 cm above the surface of the wrapping cylinder, and it bends the fiber through an angle of 35°. The average tap strength is 1.5% and the tap weights are uniform to ± 1 dB. The nonuniformity appears to be the result of tension variations. It can be reduced by improved wrapping techniques or by independent adjustment of the tension at the taps.

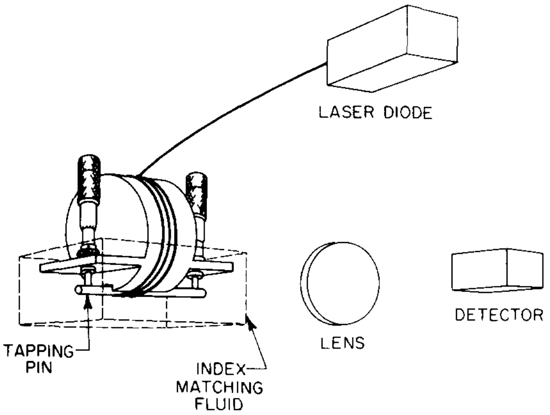

FIG. 1. Schematic diagram of fiber optic tapped delay line.

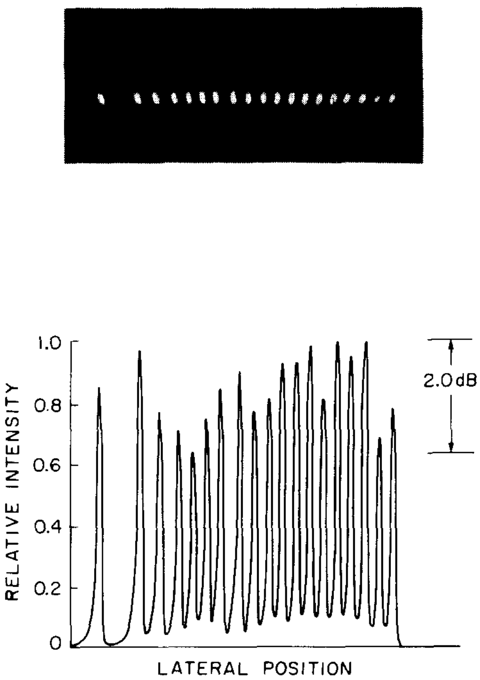

FIG. 2. Radiated tap light (top) and corresponding uniformity scan (bottom).

The delay line described above can be used as a transversal filter. The impulse response consists of a finite train of uniform delta functions separated equally in time by a delay T, which corresponds to the tap spacing. The frequency response is given by the Fourier transform which is an infinite series of sinc functions centered at 0, $1/T$, $2/T$, etc. For a 1-ns delay we expect a response consisting of a series of sinc functions centered at 0, 1 GHz, 2 GHz, etc.

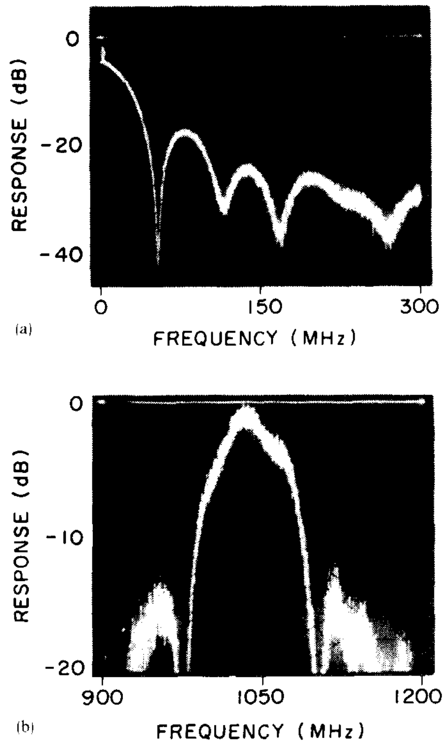

FIG. 3. (a) Frequency response of delay line with 19 taps and 1-ns tap spacing. (b) Frequency response of the same delay line near the fundamental passband (1 GHz).

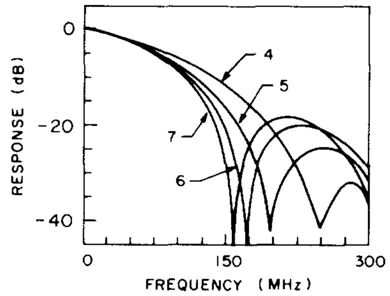

FIG. 4. Frequency response of tapped delay line operating with 7, 6, 5, and 4 effective taps.

The frequency response for the device shown in Fig. 2 is shown in Figs. 3(a) and 3(b). The frequency response was measured with an HP 8505A network analyzer. Figure 3(a) shows the response of the device from 0 to 300 MHz. The first zero occurs at 54 MHz, and the first side lobe is 13.5 dB down from the central peak as expected for a sinc function response. The unequal notch depths and irregular frequency intervals at which the notches occur are a result of the nonuniform tap weights.

Figure 3(b) shows the frequency response of the device from 900 to 1200 MHz. The central peak occurs at 1040 MHz which indicates that the actual delay time is 0.96 ns. The central peak is 22 dB down from the peak at dc. This attenuation is due to the frequency roll-off of the laser diode modulation and detector. The noise level of the measurement system is 20 dB down from the central peak.

The programmability of the transversal filter is demonstrated in Fig. 4. By physically blocking the taps so that the detector effectively samples fewer taps, one can increase the bandwidth of the central peak. The first minimum moves toward higher frequencies as the number of effective taps decreases. The experimental transfer function of the tapped delay line is shown in Fig. 4 for 7, 6, 5, and 4 effective taps. The reference for each trace was readjusted to equalize the central peaks.

In summary, we have presented an approach for making a tapped delay line which uses optical techniques to extend delay line filters to microwave frequencies. Tap uniformities of ± 1 dB have been demonstrated. Although the device described has a small number of taps, an extension of the procedure to devices with 10^2–10^3 taps is within the capabilities of the process. A simple procedure for programming the device has also been demonstrated. A more elaborate scheme using liquid crystals or optical masks as spatial attenuators could be implemented to obtain variable tap weightings. By using a large number of taps, the bandwidth can be varied in a more continuous manner than demonstrated here. The upper frequency limit for this device is determined by the frequency response of the detector and the modulation bandwidth of the laser diode. Passbands at higher harmonics could also be utilized when fast detectors and modulators are available. Finally, the minimum delay time between taps is ultimately limited only by the coherence length of the source or the maximum curvature the fiber can tolerate before significant losses occur between taps. For commercially available fiber operating at a wavelength of $0.82\,\mu$m, bending radii of 0.32 cm are possible corresponding to a 100-ps delay time or a fundamental frequency of 10 GHz.

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Real-time phase conjugate window for one-way optical field imaging through a distortion

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We demonstrate one-way optical field imaging through a distorting medium using a four-wave mixing implementation of real-time holography. Information can be transmitted at an arbitrarily fast rate as long as the mixing medium can respond to changes in the distortion.

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A number of methods for imaging through distorted media based on holography have appeared in the literature,[1–6] and more recently[7–9] imaging experiments based on phase conjugation by four-wave mixing have been performed. Imaging by phase conjugation requires that the picture field pass twice through the distortion which is a major disadvantage in the large number of practical situations where the pictorial information is to be transmitted in a single direction only. In a recent paper[10] a formal analysis was presented of a proposed four-wave mixing method for real-time one-way imaging through a distortion.

In this letter we describe and demonstrate experimentally this proposed one-way optical field imaging through distortions. The experimental arrangement is shown in Fig. 1. A transparency T contains our pictorial information to be transmitted through the distortion D. The nonlinear medium is a poled $7\times4.5\times4$ mm single crystal of $BaTiO_3$. This material is capable of supporting phase holograms of high diffraction efficiency,[11] especially when extraordinary polarization is used for the interacting beams, and the crystal is oriented in such a way as to take advantage of the very large value of the electrooptic coefficient r_{42}. Plane wave A_2 passes through T on its way to the crystal. In the crystal it encounters plane wave A_1 coming in the opposite direction as well as wave A_4 which passes first through the distortion D. The field at D is imaged into the crystal by lens L_1. For this particular experiment, the beams are from the 514.5-nm line of an argon ion laser.[12] The nonlinear mixing of A_1, A_2, and A_4 in the crystal gives rise to a new wave, A_3.

In the absence of spatial modulation on A_2, i.e., with T removed, A_3 would be the complex conjugate of A_4 ($A_3 \propto A_4^*$). In our case, however, the return wave A_3 contains pictorial information in addition to distortion information, and, on the whole, the phase conjugate property of the reflected beam has been destroyed. Nevertheless, if the returned wave is imaged onto the plane S, an image of the transparency T is recovered. The pictorial information is thus transmitted *in a single pass* from T to S.

The analysis is rather formal, so that a simple explanation of why the scheme works may be in order. By imaging the distortion D onto the crystal, say at the midplane C, we reproduce there the complex field $A_4(Q')$. The complex field at any point, say Q on C, is proportional to the field at the image point Q' to the right of the distortion D.

$$A_4(Q) \propto A_4(Q') = A_4 \exp[i\Phi(Q')], \qquad (1)$$

where $\Phi(Q')$ is the phase retardation at Q' due to the distortion and A_4 is the field of the wave impinging on the distortion from the left. The nonlinear mixing in the crystal gives rise to the polarization[13,14]

$$P(Q) \propto A_1 A_2(Q)[A_4(Q)]^* = A_1 A_2(Q) A_4^* e^{-i\Phi(Q')}. \qquad (2)$$

We note the sign reversal of $\Phi(Q')$ due to phase conjugation.

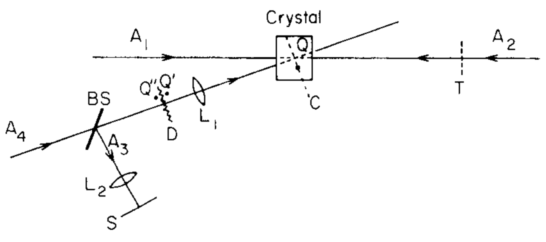

FIG. 1. Phase conjugate mirror altered to perform function of phase conjugate window. Beams 1 and 2 are the conventional pumping beams. Beam 2 carries the picture information T. The probe beam 4 passes through the distortion D which must be imaged onto the crystal by lens L_1. The reflected beam 3 carried the information through the distortion, split off at beam splitter BS, and is imaged on screen S by lens L_2.