Observation of Backward Pulse Propagation Through a Medium with a Negative Group Velocity

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The nature of pulse propagation through a material with a negative value of the group velocity has been mysterious, as simple models seem to predict that pulses will propagate "backward" through such a material. Using an erbium-doped optical fiber and measuring the time evolution of the pulse intensity at many points within the fiber, we demonstrate that the peak of the pulse does propagate backward inside the fiber, even though the energy flow is always in the forward direction.

Researchers have long been intrigued by the wide range of phenomena that can occur in the propagation of optical pulses through highly dispersive media (*1–21*). Some of the most exotic of these effects occur for a medium with a negative value of the group velocity. In such a situation, theory predicts that the peak of the transmitted pulse will exit the material before the peak of the incident pulse enters the material, and furthermore that the pulse will appear to propagate in the backward direction within the medium (*21–23*). Although the first of these effects, equivalent to the occurrence of negative time delays, has been observed by previous workers (*5*, *6*, *11*, *12*, *14*, *16*, *24*), the second of these effects has apparently not been previously observed. Indeed, it has not been entirely clear whether the theoretical prediction of backward propagation is sufficiently robust that it could be observed under actual laboratory conditions.

We report on our investigations of backward propagation of an optical pulse through an erbium-doped optical fiber (EDOF) that is pumped in such a manner as to produce a negative value of the group velocity. By measuring the time evolution of the pulse intensity at many points within the fiber, our results demonstrate that the peak of the pulse does indeed propagate in the backward direction within the fiber. However, the energy flow is always in the forward direction, as the velocity of energy transport is equal to the group velocity only under special cases, notably the absence of gain or loss in the medium (*25*).

It is useful to review the theoretical understanding of slow and fast light effects (*26*, *27*) and especially of backward pulse propagation. The group velocity describing the propagation of optical pulses through a material can be expressed as $v_g = c/n_g$, where the group index is given by $n_g = n + \omega\, dn/d\omega$, n is the usual refractive index, c is the speed of light, and ω is the frequency of the radiation. In regions of anomalous dispersion (that is, for negative values of $dn/d\omega$), the second term makes a negative contribution to the group velocity, and if this term is sufficiently large the group velocity can become negative. Negative values of the group velocity thus occur under conditions of rapid spectral variation of the refractive index, which, as a consequence of the Kramers-Kronig relations, tend to appear in regions surrounding either a narrow absorption feature or a narrow dip in a gain feature. We took the latter approach, using coherent population oscillations (*13*, *14*, *28*, *29*) (CPOs) to induce a narrow dip in the gain profile of an erbium-doped fiber optical amplifier (*30*). As we showed earlier (*13*), under these conditions the spectral variation of the gain is given by

$$g(\delta) = \frac{g_0}{1+I_0} \times \left[1 - \frac{I_0(1+I_0)}{(T_1\delta)^2 + (1+I_0)^2}\right] \tag{1}$$

where $\delta = \omega - \omega_0$ is the separation between the frequency ω at which the gain is measured and the frequency ω_0 of a strong wave of intensity I, g_0 is the unsaturated value of the gain coefficient, T_1 is the relaxation time of the population inversion of the erbium amplifier, and $I_0 = I/I_{sat}$ is the light intensity normalized to the saturation intensity I_{sat} of the erbium amplifier. The refractive index variation associated with this spectral feature is given by

$$n(\delta) = n_{host} - \frac{g_0 c T_1}{2\omega_1}\,\frac{I_0}{1+I_0} \times \left[\frac{\delta}{(T_1\delta)^2 + (1+I_0)^2}\right] \tag{2}$$

where n_{host} is the background refractive index of the optical fiber. The group index, evaluated for simplicity at the center ($\delta = 0$) of the spectral hole, is given by

$$n_g = n_{host} - \frac{g_0 c T_1}{2}\,\frac{I_0}{(1+I_0)^3} \tag{3}$$

where for EDOF the relaxation time T_1 is equal to 10.5 ms. Under our experimental conditions,

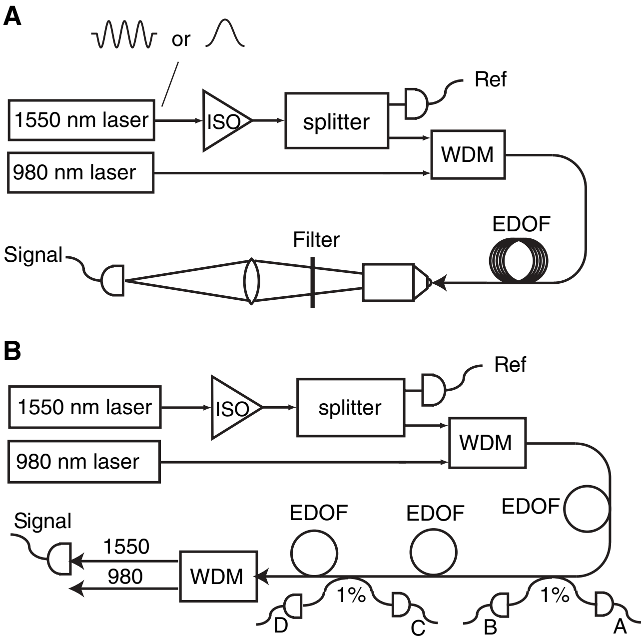

Fig. 1. (**A**) Experimental setup. The 980-nm laser acts as a pump to establish gain in the EDOF amplifier. Pulses or modulated waveforms from the 1550-nm laser probe the propagation characteristics of the fiber. A WDM combines these beams before the fiber, and an optical filter isolates the 1550-nm beam after the fiber. The time evolution of the pulse within the fiber is monitored by successively cutting back the length of the fiber and measuring the output wave form. (**B**) Alternative experimental setup used to determine the direction of energy transport in a material with a negative group index. Three 3-m sections of EDOF were placed in series, with bidirectional 1% taps placed between each pair of sections. A WDM was connected to each of the tap outputs to separate the signal wavelength from the pump wavelength. The bidirectional taps allowed measurement of energy flow in both directions.

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the measured group velocity was –75 km/s and the group index was –4000.

A group index of –4000 agrees with the predictions of Eq. 3 for a gain coefficient g_0 of 0.8 m^{-1} and a saturation parameter I_0 of 0.0032, which are reasonable estimates of the values of these parameters for our experimental setup. Even when the group index is negative, it is not necessarily easy to observe backward propagation, because this effect can be limited or obscured by competing effects such as pulse broadening and breakup as a result of dispersion of the group velocity (*31*) or by severe spectral reshaping of the pulse (*11*).

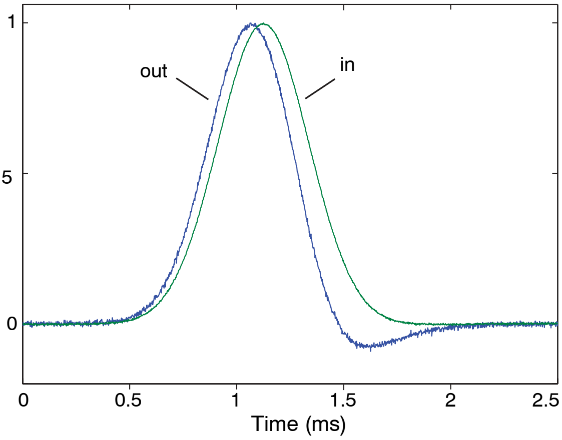
We chose an EDOF used in an optical amplifier configuration, because this enabled us to control the values of the unsaturated gain g_0 and the spectral width of the dip in the gain profile by varying the power of the 980-nm laser beam used to pump the amplifier. We were thus able to optimize the value of the time advancement associated with the group velocity (*30*). The large physical length of the material enabled us to readily measure the time evolution of the optical pulse at many locations within the fiber.

In the experimental setup (Fig. 1), the 1550-nm diode laser produces the probe pulses for our measurements. The probe laser beam is sent through an isolator, after which part of the beam is split off and sent to an InGaAs photodiode for use as a reference. The remaining light is combined with the 980-nm pump beam with the use of a wavelength-division multiplexer (WDM) and the two beams are sent through the EDOF coil. The exiting beam is collimated by a microscope objective and filtered to remove the 980-nm pump light before being focused onto a germanium photodetector. This signal and the reference are recorded by a digital storage oscilloscope.

Signal and reference traces were recorded for two different waveforms: a 1-kHz sine wave and a 0.5-ms (full width at half maximum) Gaussian pulse. In both cases, the pulse or sinusoidal waveform was superposed on a large constant background of an intensity 10 times that of peak modulation height. The presence of a large background reduces pulse distortion effects. The powers of the 980-nm pump and 1550-nm signal fields at the input to the EDOF were 128 mW and 0.5 mW, respectively. Example traces are shown in Fig. 2.

Measurements were first taken using a 9-m length of EDOF. The fiber length was then reduced by about 25 cm by cutting the fiber, and the measurement was repeated. This procedure was continued until there were only several centimeters of fiber remaining. In this way, the time evolution of the pulse could be determined at many points along the length of the fiber.

Fig. 2. Input and output waveforms after propagation through a 6-m length of erbium-doped fiber. The output waveform is seen to be advanced in time and to experience slight distortion. Pulse heights are normalized to facilitate comparison of input and output pulse shapes.



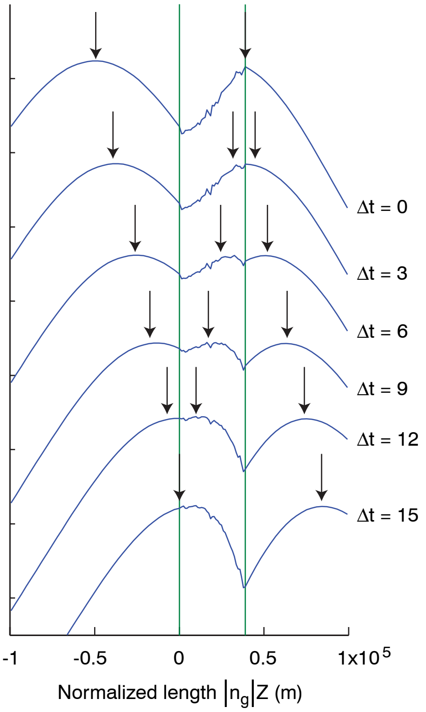


Fig. 3. Time evolution of the pulse as it propagates through the fiber. The data have been normalized at each point in the fiber to remove the effects of gain. The peak of the transmitted pulse is seen to exit the fiber before the peak of the incident pulse enters the fiber, and inside the fiber the peak moves from right to left as time increases. The arrows mark the peak of the pulse before entering the fiber (**left**), within the fiber (**center**), and after leaving the fiber (**right**). The time intervals are in milliseconds.

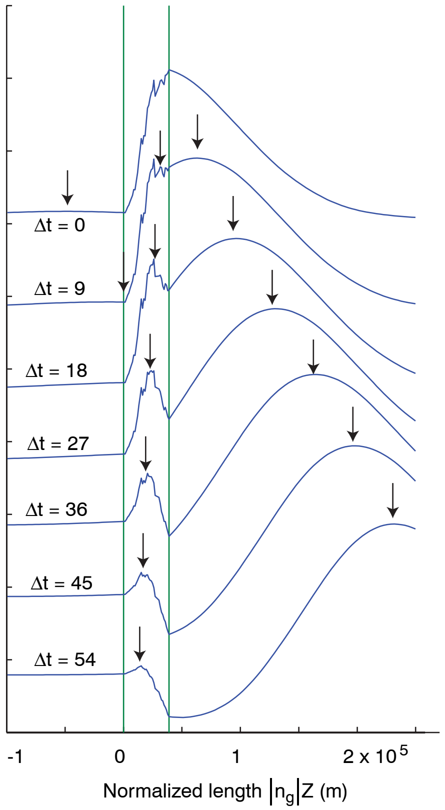


Fig. 4. Same as Fig. 3, except that the data have not been normalized to remove the effects of gain. Thus, the output pulse is much larger than the input pulse. The pulse is still seen to propagate in the backward direction, but with a different value of the pulse velocity from that of Fig. 3 as a consequence of the influence of gain. The time intervals are in milliseconds.

By arranging the traces according to position and playing them back in time sequence, we created movies showing the pulse evolution within the fiber (movies S1 and S2). Sequences of frames from these movies displaying the relevant behavior are shown in Fig. 3 and Fig. 4. In constructing Fig. 3, the waveforms at each spatial location have been normalized, removing the effects of the gain within the fiber; Fig. 4 presents the data without this normalization. In each case, the background has been removed.

In both figures, the peak of the transmitted pulse is seen to leave the fiber before the peak of the incident pulse enters the fiber. We also see that as the pulse exits the fiber, a small peak is created inside the fiber that moves in the backward direction, linking the input and output pulses. Movies S3 and S4 show similar results for a sinusoidally modulated input field. The apparent "backward propagation" occurs because of reshaping of the pulse profile within the gain medium as a consequence of time-dependent energy transfer between the pulse and the gain medium. There is no energy flow in the backward direction. Also, there is no violation of causality, as the peak that exits the material grows out of the rising edge of the input pulse, just as the peak of the input pulse becomes part of the tail of the exiting pulse.

As a further investigation into the nature of negative group velocities, we performed a second experiment to determine the direction of energy flow within the medium. The layout is shown in Fig. 1B. We observed that the signal strength measured at output ports A and C of the bidirectional 1% taps was barely above the noise floor of our detection system and was consistent with the small amount of back-reflection expected from the large number of splices present in this configuration. In contrast, strong signals were measured from ports B and D, thus demonstrating that the energy flow was only in the forward direction, even though the group velocity was negative. We also observed that the peak of the pulse arrived at port D before it did at port B, thus confirming the backward motion of the peak of the pulse within the optical fiber.

Our experiment shows that within a medium with a negative group velocity, the peak of a propagating pulse does in fact move in the backward direction, even though energy flow is always in the forward direction. These results can be understood in terms of the time dependence of the saturation of the gain of the material, whereby the leading edge of the incident pulse experiences more gain than does the trailing edge. Thus, the peak of the pulse within the medium occurs initially at the distant end of the fiber and progressively moves toward the front end of the fiber. Furthermore, all of these results are consistent with the principle of causality in that these effects are initiated by the far leading edge of the pulse.

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Supporting Online Material

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Movies S1 to S4

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Statistical Independence of Escalatory Ecological Trends in Phanerozoic Marine Invertebrates

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Ecological interactions, such as predation and bioturbation, are thought to be fundamental determinants of macroevolutionary trends. A data set containing global occurrences of Phanerozoic fossils of benthic marine invertebrates shows escalatory trends in the relative frequency of ecological groups, such as carnivores and noncarnivorous infaunal or mobile organisms. Associations between these trends are either statistically insignificant or interpretable as preservational effects. Thus, there is no evidence that escalation drives macroecological trends at global and million-year time scales. We also find that taxonomic richness and occurrence data are cross-correlated, which justifies the traditional use of one as a proxy of the other.

Major trends in the composition of Earth's biota (*1*) are widely thought to be evolutionarily important (*2*, *3*), but statistical (*4*) and taphonomic (*5*–*7*) biases might create the appearance that such trends result from ecological interactions. The publicly available Paleobiology Database (*8*) makes it possible to test (i) the strength of long-term large-scale associations between ecology and macroevolution and (ii) the assumption that global taxonomic richness is a good proxy for ecological abundance, which previously has been demonstrated only for individual groups during certain parts of the Phanerozoic (*9*, *10*).

The two most commonly cited hypotheses explaining trends in the fossil record invoke negative interactions among ecological groups. The escalation hypothesis predicts that long-term ecological shifts are caused by the evolutionary response of prey to predation pressure (*2*), which has intensified for some groups (*11*, *12*) if not others (*13*). Two potential faunal responses are progressions to infaunality (moving into the substrate for protection from predators) and mobility (evading predators on or above the subtrate, both actively and facultatively). Alternatively, the bulldozer hypothesis (*3*), a subsidiary of the escalation hypothesis, predicts that epifaunal immobile taxa will decline when there is increased biological disturbance of the sediment by infaunal, actively mobile taxa (bioturbators). Trends involving particular taxa (*14*) or over short time scales (*15*) may conform with these predictions, but these hypotheses need to be tested by examining trends in relative diversity and counts of occurrences (fossil collections that include each taxon) among marine metazoans as a whole.

We classified marine invertebrate taxa unassociated with reefs into three ecological categories (diet, life habit, and locomotion) and one preservational category (mineralogical composition) (*16*). Trilobites were excluded from analyses because their ecological trends are quite inconsistent with escalation, with their dramatic early Paleozoic decline obscuring consistent long-term trends for other groups. Thus, excluding trilobites makes our results more conservative. To avoid problems associated with variation in sampling intensity that plague estimates of global diversity (*17*), we used proportions within each ecological category instead of raw counts (*18*).

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