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Amplification of photon echo signals by use of a fiber amplifier

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The efficiency of photon-echo processes typically lies in the 0.1–1% range. For many photon-echo-based applications suggested in optical storage and all-optical communication the photon-echo output pulses would need to be used as input data to a new photon-echo process. In such cases amplification of the photon-echo output signals would be necessary for an acceptable signal-to-noise ratio to be obtained. We show that a Pr-doped ZBLAN fiber is able to produce significant amplification of photon-echo signals generated in Pr-doped Y_2SiO_5 at 606 nm.

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The photon-echo process is the time-domain approach to optical storage and signal processing based on the properties of frequency-selective optical materials.[1] The key property of data storage in frequency-selective materials is that it is possible to address selectively the atoms within different frequency intervals within the inhomogeneously broadened absorption line and then store or read a single bit of information in this frequency interval. At liquid-helium temperature there are several materials for which the number of frequency intervals that can be separately addressed within an inhomogeneous absorption line is very large, $>10^6$.[2] Storage densities in the range of terabits per square centimeter have been predicted for such materials.[3] In addition to storage density, photon-echo techniques have other unique features, especially with respect to optical processing and manipulation of temporal light sequences.[4–8]

Although there have been impressive demonstrations of storage densities, high bit rates, inherent temporal and spatial pattern recognition, and temporally based routing capabilities, many things remain to be investigated in photon-echo storage and processing. For example, there still has not been a clear demonstration of efficient bit-selective erasure of photon echoes. However, it was recently suggested that reading out the data to be erased, phase shifting them by 180 deg, and then sending them back into the sample would make bit-selective erasure possible.[9] However, because the photon-echo output intensity is generally only approximately 0.1–1% of the input intensity, it is necessary to amplify the photon-echo output pulses before sending them into the sample for the erasure process. More generally, amplification of photon-echo data is important for any process in which the output of a photon-echo process should be used as input data for a later process.

Amplification of photon-echo output pulses was previously performed by sending the echo output pulses through a YAG-laser-pumped dye amplifier.[10] The drawback to this approach was that there was gain in the amplifier only during the 10-ns-long pump pulse, whereas the input pulses had a microsecond duration. Thus the input signals could not be faithfully replicated, and also this approach could not readily be integrated into a fiber-based system. In this Letter we therefore instead look at the possibility of amplifying photon echoes by using fiber amplifiers. This would be an attractive alternative to the former approach when one is looking for compact and practical designs of photon-echo-based devices. Currently photon-echo-storage experiments are performed mainly with Pr^{3+}, Eu^{3+}, and Tm^{3+} as active ions. The most commonly used transitions are then in the wavelength regions near 600, 580, and 793 nm, respectively, leading to a serious limitation on which fiber amplifiers can be used. However, for site 1 of the ${}^1D_2-{}^3H_4$ transition in Pr^{3+}-doped Y_2SiO_5 the wavelength is 606 nm, which is only 1 nm from the peak of the roughly 10-nm-wide ${}^3P_0-{}^3H_6$ transition in Pr^{3+}-doped ZBLAN.[11] This photon-echo crystal–fiber-amplifier combination is investigated in this Letter. Although photon-echo signals, to our knowledge, were not previously amplified in fiber amplifiers, accumulated photon echoes have been generated in inverted and amplifying fibers.[12] Recently photon echoes were also observed in Er^{3+}-doped crystals at 1.5 μm,[13,14] which does give some promise of easy and efficient amplification of the output of photon-echo processors and devices in the communication wavelength region.

The experimental setup is shown in Fig. 1. The output from an argon-ion laser-pumped ring dye laser is sent through an acousto-optic modulator (AOM), producing an input pulse sequence to the liquid-helium-cooled Pr^{3+}:Y_2SiO_5 crystal. The dye laser is tuned to the site 1 ${}^3H_4-{}^1D_2$ transition at 606 nm.[2] The transmitted excitation pulses and the echo output sequence from the sample (S in Fig. 1) overlap the 476-nm beam from a second argon-ion laser and are coupled into a 29-cm-long Pr^{3+}-doped single-mode ZBLAN fiber. This fiber, produced by Le Verre Fluoré, had a Pr concentration of 2000 parts in 10^6 by weight, a core diameter of 4.5 μm, and a cutoff wavelength of 2.35 μm, so it was actually not single mode at the

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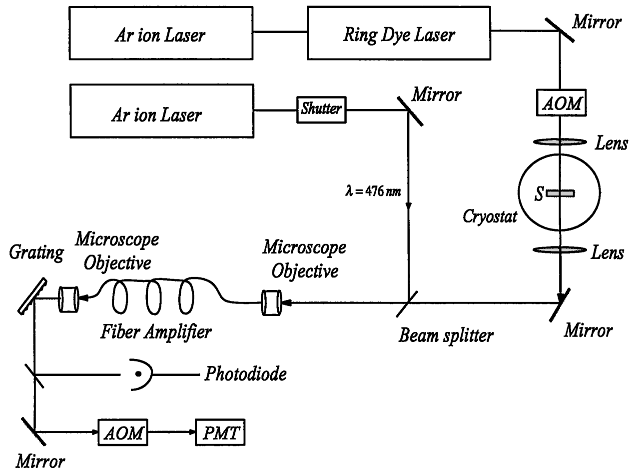

Fig. 1. Experimental setup.

606-nm signal wavelength. The 476-nm radiation will pump the praseodymium ions in the fiber from the ground state to the ^3P levels, resulting in gain on several transitions.[11] The output after the fiber was sent to a photodetector. Figure 2 shows an excitation sequence with echo output sequence after transmission through the fiber. The thinner curve is the signal with no 476-nm pump beam, and the thicker curve is the signal with 350–400 mW of 476-nm pump radiation coupled into the fiber. Because we do not prevent the input signals from reaching the fiber amplifier, the input signals also appear stronger in the thicker trace. However, in front of the Pr:Y_2SiO_5 crystal and in front of the fiber the input pulses had the same intensity in both cases. Although it cannot be seen from the figure, the amplified echo pulses are in fact still weaker than the original input pulses because of absorption in the sample and losses in and after the cryostat. Still, the potential for using the amplified echo output sequence as input pulses in a new photon-echo process is clearly illustrated. In addition to overall signal strength, the signal-to-noise ratio or signal fidelity after amplification is also important. As discussed below, the saturation intensity in this fiber should be ~75 mW. The data pulse intensity in front of the fiber was less than 10 μW; thus there is no signal-to-noise ratio degradation caused by gain saturation.

However, pumping the fiber also generates amplified spontaneous emission (ASE). The grating in Fig. 1 will remove ASE from the fiber generated at other transitions [491, 520, 635, and 715 nm (Ref. 15)]. The acousto-optic modulator in front of the photomultiplier tube (PMT, Fig. 1) is normally closed to protect the photomultiplier tube from the radiation from the 605-nm ASE but opens during the excitation sequence. In the present case the signal bandwidth is ≈1 MHz; thus further spectral filtering (possibly with a spectral hole-burning notch filter[16]) of the 605-nm ASE, which has a bandwidth of several nanometers, or coherent detection would decrease or even practically eliminate the ASE background. In fact, because the inhomogeneous linewidth in the praseodymium crystal is of the order of 4 GHz, only ~0.1% of the ASE signal will fall within the Pr:Y_2SiO_5 transition. Further, because the ASE signal is incoherent, it will be extremely inefficient in generating an echo signal; in addition, the ASE background will be eliminated in any subsequent photon-echo process that uses a noncollinear excitation scheme.

For the Pr:ZBLAN fiber the highest gain transition occurs at 635 nm. The ≈4% reflection at the end surfaces of the fiber causes the fiber to start lasing when the single-pass gain $\exp(N\sigma_{635}L)$ is ~25, where N is the number of atoms per unit volume in the upper laser level (the thermal population in the lower laser level is negligible compared with the density of upper-state atoms needed to reach the lasing threshold), L is the fiber length, and σ_{635} is the emission cross section for the 635-nm $^3P_0 - ^3F_2$ transition. As the 635-nm and the $^3P_0 - ^3H_6$ 605-nm transitions have the same upper state, the gain at the 606-nm Pr^{3+}:Y_2SiO_5 transition will essentially equal $\exp(N\sigma_{606}L)$. 606 nm is quite close to the peak of the Pr:ZBLAN 605 nm transition, and in total the cross section at 606 nm is ~75% of the 635-nm transition cross section.[17] Pumping above the 635-nm threshold results in lasing at 635 nm, which clamps the $^3P_0$ population level to the threshold value when the pumping intensity is further increased. Thus the maximum single-pass gain at 606 nm becomes roughly a factor of 10. In our experiment we tested a double-pass configuration with higher gain by butting a mirror transparent to 635 nm but reflecting 606 nm to one end of the fiber. However, the double-pass gain at 606 nm, including losses in the mirror, had to be kept below 25 times to avoid laser action at 606 nm. (Laser action at 606 nm would clearly destroy any information present at this wavelength.) In fact, the configuration with a mirror transmitting 635 nm and reflecting other wavelengths was limited to amplification values slightly below a factor of 25 owing to laser action at 715 nm on the high-gain $^3P_0 - ^3F_4$ transition.

The main reason for amplifying photon-echo pulses is to be able to use them as input pulses to other photon-echo processes. As the efficiency in photon-echo data storage or processing typically would be approximately 0.1–1%, the total gain will preferably be in the region 100-1000 times. To increase the gain we cut the fiber ends at an angle of ~10°, thus preventing the reflections from the end from getting

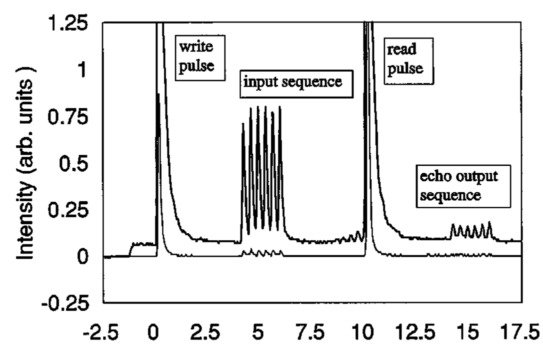

Fig. 2. Experimental trace, demonstrating amplification of photon-echo signals in a praseodymium-doped ZBLAN fiber. Thinner curve, unamplified signal; thicker curve, amplified signal.

coupled back into the fiber core. This was the configuration that we used to obtain the traces in Fig. 2. With ~400 mW of 476-nm radiation coupled into the fiber core the single-pass gain was ~45 times. A later experiment showed that cooling half of the 29-cm-long fiber to 77 K increased the gain by more than a factor of 2 for a given pump power. The optically pumped population in the $^3P_0$, $^3P_1$, and $^1I_6$ manifolds thermalizes on a picosecond time scale, so at 77 K the fraction residing in the lowest $^3P_0$ state, which is the upper level of the amplifier transitions, is substantially increased over the room-temperature value. Cooling to cryogenic temperatures normally would be a rather unattractive option. But for photon-echo storage and processing the photon-echo crystal is already held at cryogenic temperature, and other system components could be integrated into the cryogenic part of the device. Thus, cooling the fiber combined with a double pass could in principle yield an overall gain close to 8000 if parasitic lasing could be eliminated. However, in practice the upper limit to the gain ($\Gamma_{\max}$) achievable from an optical amplifier is reached when amplified spontaneous emission begins to saturate the gain. This point is determined by geometrical factors (see, e.g., Ref. 18, Chap. 13.8) and for a fiber amplifier is approximately given by $\Gamma_{\max} \sim 4n^2/(\mathrm{NA})^2$, where n is the index of refraction of the core and NA is the numerical aperture of the fiber. The NA of the fiber used in our experiments is ~0.4; with $n \approx 1.5$ the maximum gain would fall between times 50 and 60. Clearly, by using low-NA fiber, one could increase this value by an order of magnitude. It is also important to know what power can be provided by the fiber. Typically the input power in photon-echo storage and processing experiments in rare-earth-ion-doped crystals would be in the range 1–10 mW. The saturation power P_{sat} equals the saturation intensity, I_{sat}, times the fiber area. I_{sat} can be calculated from $I_{\mathrm{sat}} = h\nu/\sigma_{605}\tau$, where τ is the $^3P_0$ state lifetime. With $\sigma_{605} \approx 1.5 \times 10^{-24}\ \mathrm{m}^2$ and $\tau = 47\ \mu\mathrm{s}$,[17,19] $P_{\mathrm{sat}} \approx 75$ mW. Consequently the fiber can normally be operated significantly below the saturation power.

Most photon-echo-based applications would in practice require diode-laser-based sources. Infrared diodes might provide practical alternatives to the argon-ion laser as pump sources through visible upconversion. Single-wavelength pumping has been demonstrated in Pr:fluoride fibers codoped with ytterbium ions.[20,21]

Much interest is concentrated on the Tm:YAG crystal at present. This crystal has a transition with a long homogeneous dephasing time that is suitable for photon-echo applications at 793 nm, an excitation wavelength readily accessible by diode lasers. A fiber amplifier operating at 793 nm would be interesting, although laser diodes may also offer amplification at this wavelength. Thulium ions in ZBLAN glass have been used for amplification at 806 nm.[15] This is a quasi-three-level amplifier, in which the fluorescence band overlaps the corresponding absorption band, with absorption peaking at the 795-nm pump wavelength. Amplification at wavelengths shorter than 800 nm has to our knowledge not been reported in this system. The reason is probably the strong reabsorption from the ground-state manifold. However, calculations indicate that useful gain at 793 nm would be achievable with a strong pump near 775 nm.

In conclusion, we have demonstrated amplification of photon-echo signals in a praseodymium-doped fiber amplifier. This development can be expected to broaden significantly the application area of photon-echo-based devices (e.g., optical bit-rate converters, routers, and erasable memories) in situations in which the photon-echo output is used as an input for a new photon-echo process.

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