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Ge-doped Raman fiber amplifier with enhanced signal-to-noise ratio using second Stokes control pulses

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Abstract. A Ge-doped Raman fiber amplifier with enhanced signal-to-noise ratio is numerically analyzed using second Stokes control pulses. Inter-pulse noise power in the signal to be amplified is moved to the second Stokes pulse and therefore the signal-to-noise ratio for the amplified signal pulse is enhanced. The effects of different kinds of second Stokes pulse on the signal are reported.

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Raman fiber amplifiers (RFA) [1–24] and Raman fiber lasers [3, 4, 25–27] have been extensively studied since the 1980s, but it came to an abrupt end with the advent of the Er-doped fiber amplifier (EDFA) in the early 1990s. The development of high-power fiber lasers has created a renewed interest in RFAs.

RFA has been used as discrete [28, 29], analog, and digital amplifiers at both 1.3 μm [2] and 1.5 μm [5, 8, 12, 30] and as remotely pumped amplifiers in the repeaterless optical communication systems [31, 32]. A recent new application in the field of optical fiber amplifiers is a hybrid optical amplifier, using both Er-doped and Raman fiber amplifiers, which has very wide 3-dB bandwidth of 90.5 nm [10].

Large signal-to-noise ratio (SNR) is an essential factor in high-speed optical transmission to get a low bit-error-rate (BER). During optical amplification, noise is also amplified due to the amplified spontaneous emission (ASE) and other effects and limits the performance of the DWDM optical transmission system. To reduce the noise level, a mid-stage isolator or an attenuator, or a fiber Bragg grating have been applied in some optical amplifiers. These components reduce the noise in the spectral domain. Usually, the SNR is reduced to less than a half of the input SNR and the noise figure is larger than 3 dB [33].

As germanium-doped fibers with 20 mol % have a large Raman gain coefficient and are not very lossy, they are used extensively in RFA. RFA consists of a pump laser and a signal pulse at the first Stokes wavelength Raman-shifted from the pump wavelength that is to be amplified.

We propose a new idea to reduce the noise level in the temporal domain with help of the Ge-doped Raman fiber amplifier (GDRA) and control pulses at the second Stokes wavelength.

First, description and theoretical background of the new idea is expounded. Second, the results and discussion of the numerical simulations are reported. Finally, brief conclusions are presented.

1 Background

A major contribution to the noise is due to amplification during inter-signal pulse times and this prevents the lowering of the decision level for a data stream. When there is high level of “ON” signal, ASE is not amplified significantly, whereas when there is low level of “OFF” signal, the ASE increases drastically. Therefore, noise reduction can be achieved if the noise power between the signal pulses is reduced or transferred to another wavelength.

Our idea is to transfer the noise power between the signal pulses to the power of the control pulses as shown in Fig. 1a–e. Without control pulses, both the “ON” and “OFF” signal pulses are amplified as we see in Fig. 1d. Whereas when “ON” control pulse is applied for “OFF” signal pulse, the power of the amplified “OFF” signal-pulse is transferred to the control pulses due to the interaction of the pump by the SRS. For the “ON” pulse in the signal, “OFF” pulse in the control pulses is applied so that the power of the amplified “ON” signal-pulse is not changed. Therefore, the noise level is reduced using the control pulses and we get the high SNR for the signal as shown in Fig. 1e.

Figure 2 shows the setup for the GDRA analysis. Lights from three sources co-propagate in the Ge-doped fiber (GDF) and interact with themselves to result in Raman amplification. The equations governing the interaction of the pump (I_P), the first Stokes (I_{S1}), and the second Stokes (I_{S2}) intensities are

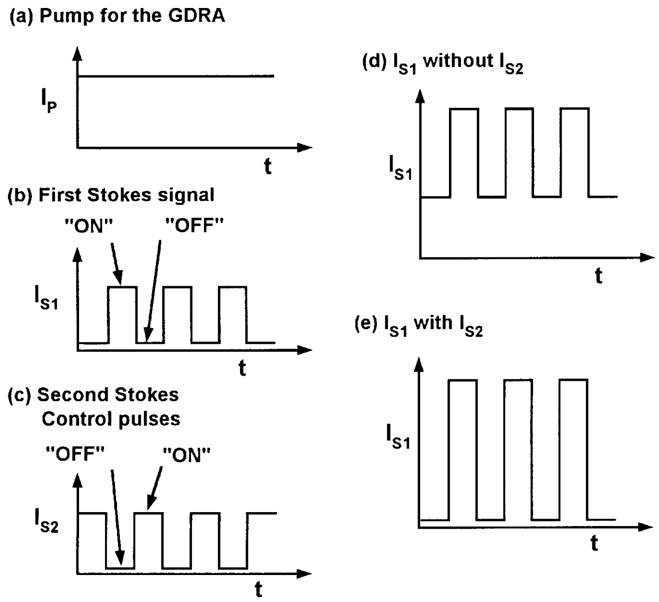

Fig. 1. Concept of the noise filter for the Raman amplification with the second Stokes control pulses. I_P, I_{S1}, and I_{S2} are the pump, the first Stokes, and the second Stokes intensities, respectively

given by the following coupled equations:

$$dI_P/dz = -(\omega_P/\omega_{S1})g_R I_{S1} I_P - \alpha_P I_P \ , \tag{1}$$

$$dI_{S1}/dz = g_R I_{S1} I_P - (\omega_{S1}/\omega_{S2})g_R I_{S2} I_{S1} - \alpha_{S1} I_{S1} \ , \tag{2}$$

$$dI_{S2}/dz = g_R I_{S2} I_{S1} - \alpha_{S2} I_{S2} \ , \tag{3}$$

where g_R is the Raman gain coefficient, and α_P, α_{S1}, and α_{S2} are the fiber loss coefficients at the pump, the first, and the second Stokes wavelengths, respectively. ω_P, ω_{S1}, and ω_{S2} are the frequencies of the pump, the first, and the second Stokes lights, respectively. Since g_R refers to Raman gain of the Stokes power, the pump power loses more power up to the ratio of ω_P/ω_{S1} due to balance of photon numbers as shown in (2). The same rule is applied to the second Stokes power as shown in (3).

2 Results of the numerical simulations

In our analysis we used 1 W at 1453 nm for the pump light, 0.562 μW (− 32.5 dBm) at 1555 nm for the "ON" signal pulses and 50 mW at 1665 nm for the "ON" control pulses. In the usual fiber optic systems, when the signal power reduces to about − 32.5 dBm, it can be detected and reamplified in the receiver side. The power levels of the signal and the control pulses are inverted to each other in the simulation. As the Raman gain, $g_R^{Ge} = 1.084 \times 10^{-11}$ cm/W is used for 20 mol % GeO_2-doped fiber which is calculated using $(1 + 0.080\Delta)g_R^{Si\text{-}SMF}$ where Δ is the relative refractive-index difference and $g_R^{Si\text{-}SMF}$ is a Raman gain for a silicate single-mode fiber [20]. The loss coefficients of α_P, α_{S1}, and α_{S2} are used by 0.227, 0.173, 0.232 dB/km, respectively.

Figure 3 shows the axial power evolution along the fiber length. Figures 3a and 3b show that when there is no control pulse such as $P_{S1}(\text{OFF}) = 0$, 79% of the pump power is transferred to $P_{S1}(\text{ON})$ at 850 m and $P_{S1}(\text{OFF})$ powers at 1080 m, respectively. As we see in Fig. 3c and 3d which use $P_{S2}(\text{ON}) = 50$ mW, the maxima of the signal "ON" and "OFF" power are 74.7% at 850 m and 53.9% at 1080 m, respectively. In the latter case, more than 84% of the pump power is transferred to the power of the second Stokes "ON" pulse at 1530 m.

Figure 4 shows the axial evolution of the SNR with and without the control pulses (I_{S2}). Larger SNR is obtained when the control pulses (I_{S2}) are used. With no control pulse, the SNR decreases monotonically with increase in fiber length. With the use of control pulse, the SNR is maximized to 164.8 (1.73 times more than the "no control pulse" case) at 560 m. At this fiber length, the amplified signal power of $P_{S1}(\text{ON})$ is 38.9 mW with 48.4 dB gain.

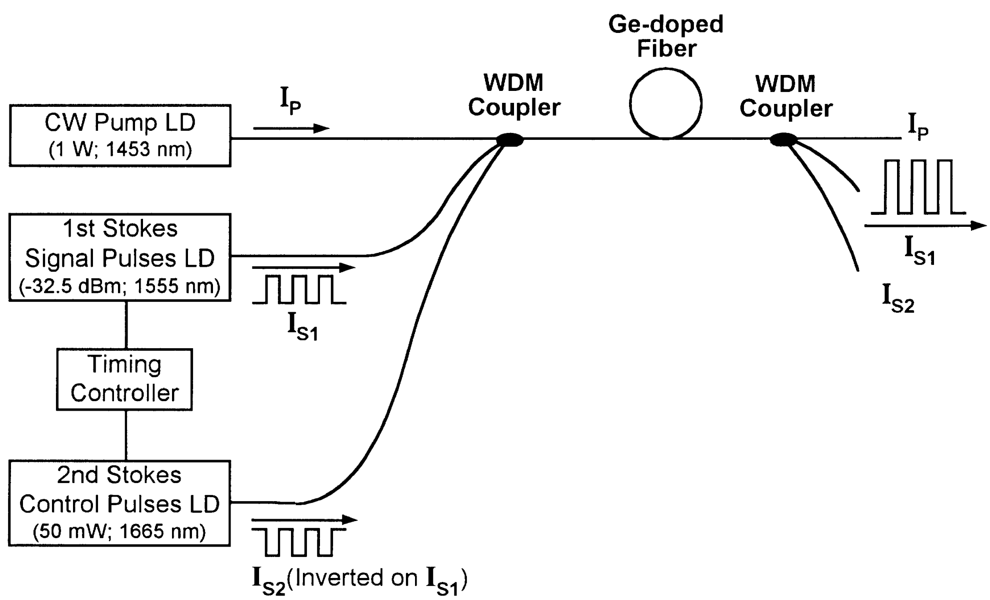

Fig. 2. Setup for the Ge-doped Raman fiber amplifier with the second Stokes pulses. I_P, I_{S1}, and I_{S2} are the pump, the first Stokes, and the second Stokes intensities, respectively. The timing controller is to control the phase of the first and the second Stokes pulses

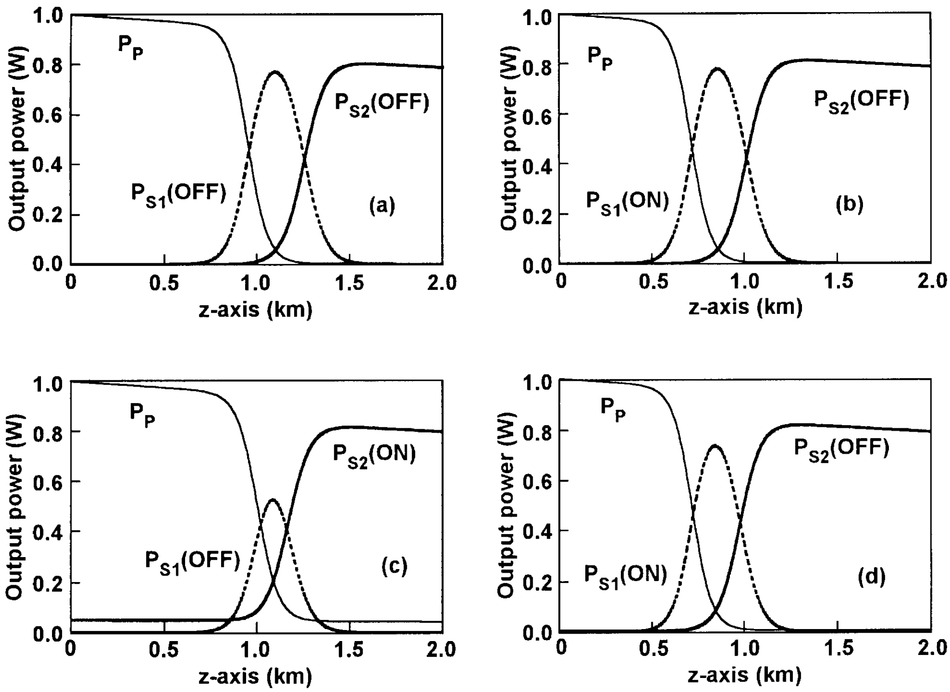

Fig. 3. Evolution of the pump, the first Stokes, and the second Stokes powers along the fiber length. P_P, P_{S1}, and P_{S2} are the pump, the first Stokes, and the second Stokes powers, respectively

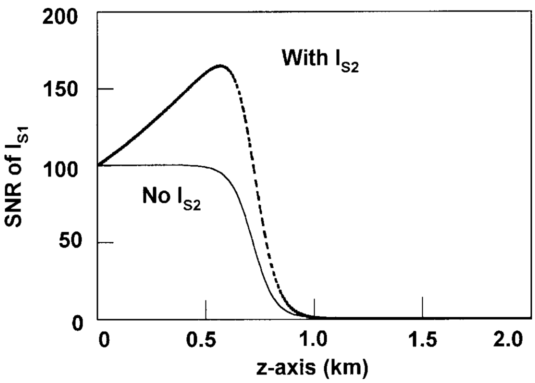

Fig. 4. Evolution of the SNRs with and without the second Stokes control pulses. I_P, I_{S1}, and I_{S2} are the pump, the first Stokes, and the second Stokes intensities, respectively

In real situations, one is unsure of the signal pulse train and the use of an inverted control pulse is practically impossible. To overcome this problem, a detailed study with three different kinds of control pulse is presented. The three types of control pulses are

(i) an inverted clock pulse with the same pulse width as thesignal pulse,
(ii) an inverted clock pulse with widened pulse width for the signal pulse width, and
(iii) continuous wave (cw) control light.

In our analysis, all the calculations were made for a fiber length of 780 m for different control pulses since it makes the most efficient conversion efficiency. The simulations were done for two kinds of signal pulses,

(a) carrier data pulse (recurring ON and OFF pulses, like 01010...) and
(b) real data pulse (random “ON” and “OFF” pulses, like 010010...).

Figure 5 shows the results when no control pulse is applied. As we see in Fig. 5d, the SNR for the real data pulses is 11.27 after Raman amplification.

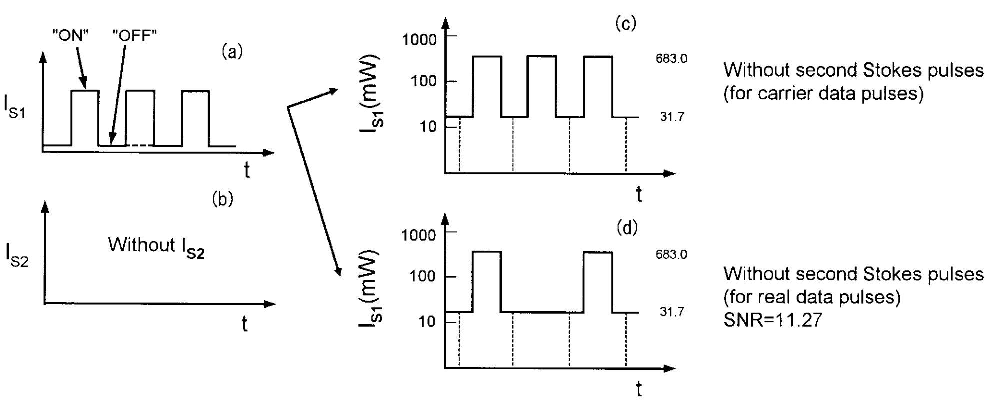

Fig. 5. GDRA without the second Stokes control pulses

Figure 6 is for the case (i) in which the inverted control pulse, with respect to carrier data pulse, is used on the carrier data and real data. Figure 6c shows the amplification of the carrier data pulses, whereas Fig. 6d is for real data pulses. The use of the inverted control pulses has increased the SNR by 30.1%, which value is 14.66 and made a higher gain of 60.6 dB. In the position of the "OFF" signal pulses which encounter an "OFF" control pulse, a small pulse (2.75% of the amplified "ON" pulse) is produced due to mismatch, but this can be made harmless by taking a slightly higher decision level.

Figure 7 shows the results for the case (ii) in which an inverted and widened control pulse is used with respect to the carrier data pulse. The results are similar to the case (i) except that the pulse shape for the amplified "ON" carrier and real data pulses have a slight change as shown in Figs. 7c and 7d. But in the case of real data, along with this change in pulse shape for the "ON" pulses, the pulse width of the OFF signal pulses is reduced down to 50% of the original signal pulse. However, it increases the SNR by 34.8% from the one when the control pulse is not used. Also, there is still high gain of 60.0 dB.

As shown in the case (iii) in Fig. 8, in which we use a cw control light in the FRA, it shows a slight decrease in gain (59.2 dB) but the SNR is increased up to 17.14 and is 52.1% better than the case when no control pulse is used.

3 Conclusion

We have proposed and theoretically studied a new mechanism of all-optical amplifying noise filter to enhance the SNR based on the SRS. The basic idea is to transfer the temporal background noise power in the first Stokes wavelength to the second Stokes power by using the SRS. Of the different control pulses at the second Stokes wavelength, the use of

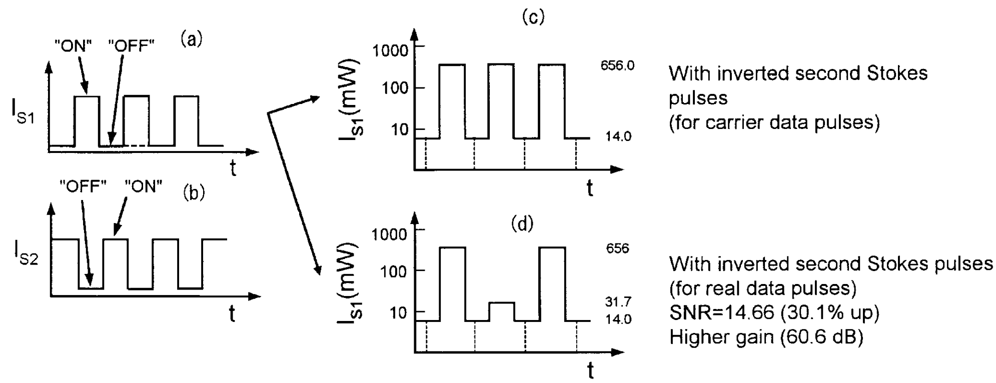

Fig. 6. GDRA with the inverted second Stokes control pulses

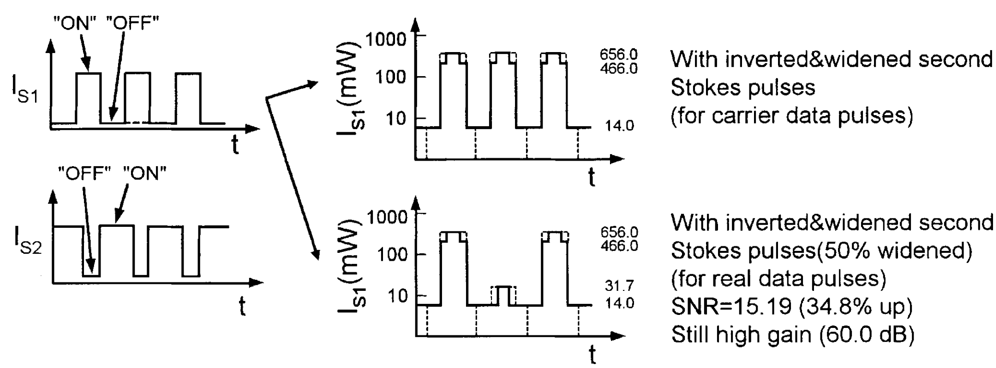

Fig. 7. GDRA with the inverted and widened second Stokes control pulses

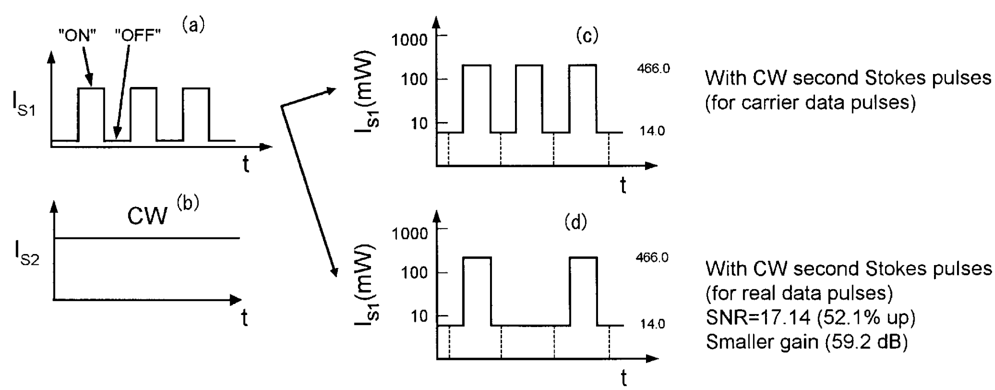

Fig. 8. GDRA with the cw second Stokes control light

cw has a slight decrease in gain but instead has 52.1% SNR enhancement compared to the case when no control pulse is applied. In our opinion this can improve the sensitivity of the RFA. The pump source with cw 1 W power level and 1453 nm wavelength is now available in the commercial market and the first and the second Stokes pulses at 1555 nm and 1665 nm, respectively, are also available. The inverted pulses can be generated with the help of a timing controller as shown in Fig. 2. Therefore, our proposed scheme may be experimentally confirmed in the near future.

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