All-Optical 2R Regeneration Based on Similariton Generation in HNL-PCF for High Bit Rate Networks

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Abstract— **This paper presents an advanced all-optical 2R regenerator based on optical similariton generation in a custom-designed highly nonlinear photonic crystal fiber (HNL-PCF) amplifier. The HNL-PCF is optimized for high nonlinearity and low dispersion, enabling efficient similariton formation. The proposed scheme suppresses ASE noise and restores signal integrity across data rates from 40 Gb/s to 160 Gb/s. Compared to recent 2R regenerators based on self-phase modulation (SPM), our system demonstrates superior performance, offering enhanced noise suppression and signal quality. Integrated into a high-speed optical link, it significantly improves signal quality, highlighting its potential for next-generation optical networks.**

Keywords—All-optical 2R regenerator, Raman amplification, optical similariton, high-capacity optical networks.

I. Introduction

The rising demand for high data rates in modern optical networks makes all-optical signal regeneration vital for maintaining transmission quality. Unlike electronic regeneration, which involves optical-electrical conversion, all-optical methods keep signals in the optical domain, offering higher bandwidth, lower latency, and better energy efficiency. Among these, 2R regeneration combining reamplification and reshaping offers a good trade-off between complexity and performance [1]. Self-phase modulation (SPM) is often used in such systems, with the Mamyshev regenerator standing out for its simplicity [2]. However, SPM-based methods encounter issues like spectral ripples and instability at high bit rates. This work presents a 2R regeneration approach based on optical similariton pulses, which exhibit smooth spectral broadening and linear chirp. These features improve amplitude noise suppression and reduce timing jitter. The method is implemented in a Raman-amplified highly nonlinear photonic crystal fiber (HNL-PCF) and evaluated at 40, 80, and 160 Gb/s. Results show superior performance over conventional SPM regenerators in terms of signal quality, jitter reduction, and transmission stability.

II. Simulation and Results

A. *Generation of Optical Similariton Pulses*

Figure 1 shows the simulation setup used to generate optical similariton pulses in a silica-based Raman amplifier HNL-PCF, implemented using OptiSystem. Numerical modeling, carried out using the Finite Element Method (FEM) guided the optimization of parameters to achieve efficient pulse shaping and stable similariton formation [3]. The optimized configuration includes an input pulse power of 1 W, pulse duration of 0.2 ps, fiber dispersion of −1.53 ps/(nm.km), nonlinear coefficient $\gamma = 41\ \mathrm{W^{-1}\cdot km^{-1}}$, and Raman gain coefficient $g_R = 7.6 \times 10^{-13}$ m/W.

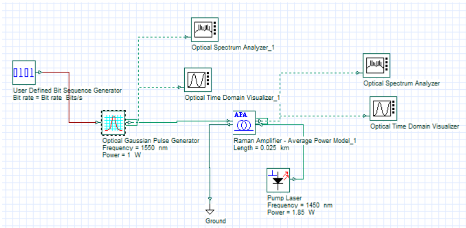
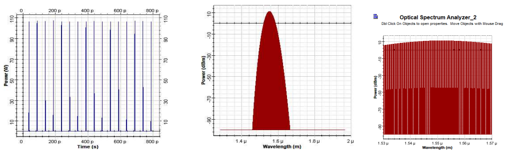


Fig.1: Schematic of the setup for generating optical similariton pulses at 1550 nm in the modeled HNL-PCF (25 m). Simulation parameters: input power P_0=1W, pulse duration T_0 = 0.2 ps, dispersion D = −1.53 ps/(nm.km), nonlinear coefficient $\gamma = 41\ \mathrm{W^{-1}\cdot km^{-1}}$, and Raman gain coefficient $g_R = 7.6 \times 10^{-13}$ m/W.

Figure2 shows that an input train of Gaussian pulses evolves into a train of optical similaritons after 25 meters of amplification. The resulting spectrum demonstrates excellent flatness, with minimal power variation across a 40 nm bandwidth effectively covering the C-band of the third optical telecommunications window. The output peak power reaches 104.6 W, reflecting strong pulse shaping and efficient nonlinear interaction.



(a) (b) (c)

Fig. 2: Temporal (a) and Spectral (b)Profiles of Similariton Pulses generated in a Raman-Enhanced HNL-PCF (L=25 m, P_0=1 W, T_0=0.2 ps, D=–1.53 ps/(nm.km), γ=41 $\mathrm{W^{-1}km^{-1}}$, g_R=7.6×10^{-13} m/W at 1550 nm). (c) Zoomed-in view of the central part of the spectrum shown in (b)

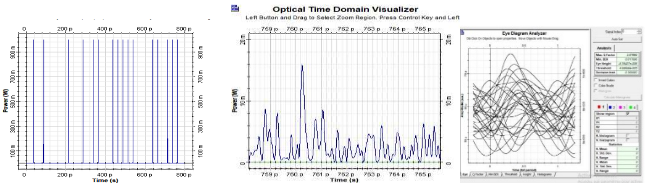
B. *Performance Analysis of High-Bit-Rate Optical Links Without Signal Regeneration*

A 40 Gb/s optical transmission system over 50 km was simulated in OptiSystem 7.0, using 1 W input pulses to intentionally degrade the signal and demonstrate the effectiveness of the all-optical 2R regenerator. An EDFA (gain: 16.3 dB) compensates for attenuation, and a variable optical attenuator manages power levels. The transmission span consists of standard single-mode fiber (SMF) and dispersion-compensating fiber (DCF), with parameters summarized below.

Figure 3 shows severe signal degradation in the transmission link without regeneration, as evidenced by a closed eye diagram and a low quality factor of Q = 2.

Table1: Transmission link parameters

Fiber	*D* *(ps/(nm.km))*	S_D *(ps/(nm²km))*	A_{eff} *(µm²)*	*α* *(dB/km)*
SMF (G652)	16.75	0.075	80	0.2
DCF	-80	0.21	27	0.6



(a) (b) (c)

Fig. 3: (a) Input optical signal; (b) Signal shape at the output of a 400 km, 40 Gb/s transmission link without regeneration; (c) Eye diagram of the received signal.

C. *Performance Analysis of 2R Regeneration with Similariton Pulses*

Figure4 illustrates the simulation setup of the proposed 2R regenerator based on optical similariton pulses. The degraded signal from the 400 km link is first amplified using an optical amplifier with a gain of 18 dB to reach 1 W, then filtered with a 60 GHz Gaussian filter centered at 1550 nm, and further optimized using a 2.25 m SMF segment to reduce residual chirp.

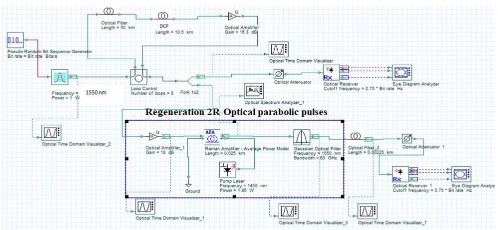
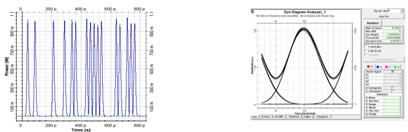


Fig. 4: 2R Optical Regeneration Setup using similariton pulse generation in a Raman- HNL-PCF amplifier

Figure 5 shows that after 2R regeneration using parabolic pulses at 40 Gb/s, the signal exhibits a fully open eye diagram with a quality factor improvement from Q = 2 to 81.85, highlighting effective noise suppression at the zero level and reduced intensity fluctuations in the "1" bit.



(a) (b)

Fig. 5: (a) Temporal Profile and (b) Eye Diagram of the regenerated signal for a 40 Gb/s, 400 km link

D. *Comparison Between SPM-Based Regeneration and 2R Optical similariton Pulse Regeneration*

The SPM-based regenerator restores degraded signals by amplifying them to induce spectral broadening in a normal dispersion fiber. This process is followed by filtering out ASE noise and injecting the signal into a band-pass filter, whose center frequency is calculated using the relation $\omega_f=\omega_0+\Delta\omega_{spm}$ where $\Delta\omega_{spm}=\Delta\omega_0(2\pi/\lambda)\, n_2 I_p L$, ω_0 is input signal bandwidth, pulse intensity is denoted by I_p, n_2 is a nonlinear refractive index, λ is the wavelength and L is the length of nonlinear medium. [4]. The SPM regeneration process was simulated using OptiSystem,. If $\omega_{spm}/2<\Delta\omega_{shift}$, the pulse is rejected by the optical filter, which occurs when the pulse intensity I_p is very small, representing noise in the "zero" state. If the pulse intensity is sufficiently high so that $\omega_{spm}/2 \geq \Delta\omega_{shift}$, the broadened pulse passes through the filter.

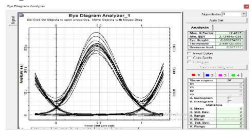


Fig. 6: Eye Diagram of the signal regenerated by the spm-based regenerator for a 40 Gb/s, 400 km Link

Figure 6 shows the regeneration of a degraded signal using the SPM-based regenerator, reducing noise but with some intensity fluctuations and temporal jitter, yielding a Q factor of 12.48 at 40 Gb/s much lower than the seven-fold improvement seen with optical parabolic pulse regeneration.

E. *Impact of Bit Rate and Transmission Length on Optical Similariton Pulse Regeneration*

Figure 7 illustrates the impact of bit rate and transmission distance on signal quality, showing how the quality factor (Q) decreases with increasing bit rate and distance due to nonlinear effects and chromatic dispersion.

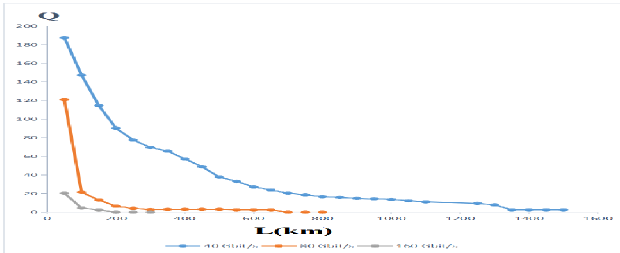


Fig. 7: Q-Factor vs. Distance – similariton 2R regenerator for (40Gbit/s-80Gbit/s-160Gbit/s).

III. Conclusion

An all-optical 2R regenerator based on similariton pulses was implemented using a Raman-enhanced HNL-PCF. It achieved a Q factor of 187.48 at 40 Gb/s and maintained Q greater than 6 up to 1300 km. These results confirm its strong potential, to be further highlighted through comparison with conventional SPM-based regeneration.

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