Multilevel amplitude regeneration of 256-symbol constellation

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We propose a novel scheme for multilevel (9 and more) amplitude regeneration based on nonlinear optical loop mirror and demonstrate its efficiency and cascadability on 256-symbol constellation.

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1. Introduction

The optical signal regeneration in fiber-optic communications can provide efficient reduction of both noise and nonlinearity impairments, enabling high capacity transmission [1-5]. One of the important challenges for optical regeneration is to offer new schemes capable to regenerate multi-level higher order advanced modulation formats used in coherent optical communications [6]. A nonlinear optical loop mirror (NOLM) is a well-known device used for an efficient amplitude regeneration [3-5]. The cascadability of NOLM in long-haul transmission applications was experimentally demonstrated. However, the existing NOLM-based schemes are typically limited for up to 2 amplitude levels [4].

Here we propose a novel scheme based on the NOLM coupled with the input signal. This enables multilevel amplitude regeneration (9 or more levels). Also, the corresponding phase shift associated with the transformation is significantly reduced (compared with the traditional NOLM schemes) and can be sign-reversed by a simple change of transformation parameters. Furthermore, the scheme provides more degrees of freedom for optimization by introducing additional coupling factor. This can be relevant for optimizing the number of regenerative levels, as well as, their positioning. We demonstrate the feasibility of the proposed technique using as an example 256-symbol constellation in the efficient amplitude regeneration.

2. Design

The initial signal $A_{in} = \sqrt{P_{in}}e^{i\varphi}$ is split by 3dB coupler and then one of the waves is transformed by the NOLM. Then, two waves (output of the NOLM and the second wave of the first coupler rotated by $\Delta\phi = 3\pi/2$) are coupled by the second coupler with the power ratio between them being κ^2. The obtained wave is amplified by 2 to restore the initial power (see the scheme in Fig.1(a)). The resulting total transfer function is expressed via the initial field as:

$$A_{out} = \sqrt{P_{out}}e^{i(\varphi+\delta\phi)} = \left(1 + i\kappa\left(-(1-\alpha)e^{i(1-\alpha)\gamma L P_{in}/2} + \alpha e^{i\alpha\gamma L P_{in}/2}\right)\right)\sqrt{P_{in}}e^{i\varphi} \qquad (1)$$

where α denotes the coupling ratio, L is the length of highly nonlinear fiber, and γ is fiber nonlinear coefficient. As a result of the transformation the transfer function (TF) of the output power versus the initial power has multiple plateau regions around the given stationary and stable points of the transformation. The dimensionless output power P_{out} and phase shift $\delta\phi$ versus the normalized initial power P_{in} for parameters $\alpha = 0.267$; $\kappa = 0.014$ are shown in Fig.1(b-c) correspondingly.

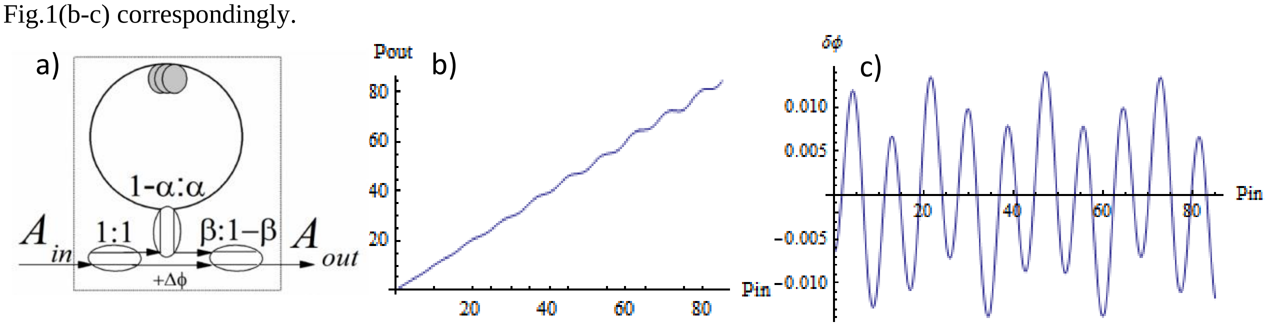

Fig1. (a) Scheme; (b) TF for the dimensionless output power normalized by $\gamma L/2$ and (c) associated phase shift for parameters: $\alpha = 0.267$; $\Delta\phi = 3\pi/2$; $\kappa = \sqrt{\beta/(1-\beta)} = 0.014$

3. Results

We simulated numerically the transmission performance of the proposed regenerative schemes using as an example of circular 256-symbol constellation, where amplitude levels were defined by the stationary and stable points of the

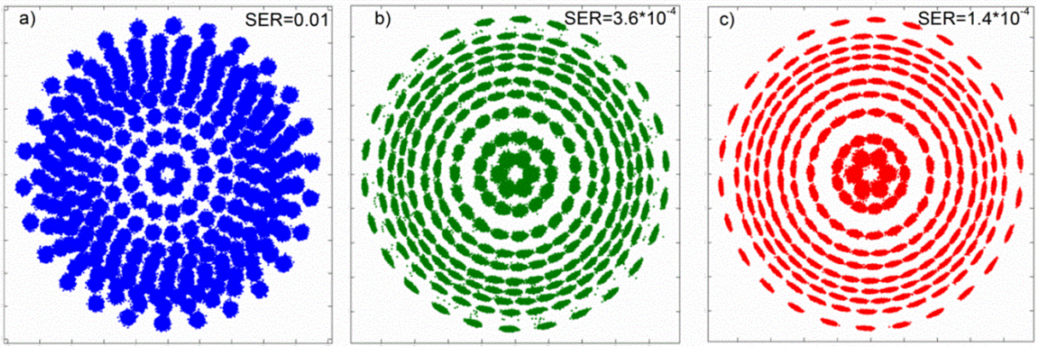

Fig2. Constellation diagrams for 256 circular QAM after transmission (a) without and with (b)10 and (c)20 equidistantly placed regenerators (see Fig.1 with $\gamma L = 2W^{-1}$) with OPC placed in the middle of the transmission line. In the absence of regeneration the linear system has SNR=30dB.

amplitude transfer function (determined by the method of [7]), whereas the phase distribution was chosen the analogues 256- iterative-polar-modulation (IPM) circular quadrature amplitude modulation (QAM) [8]. The signal was transmitted through a cascade of regenerative devices interleaved with uniformly distributed additive white Gaussian noise. The noise impairments were estimated by signal-to-noise ratio (SNR) in the corresponding linear system in the absence of regeneration. This gives a reference value of SNR, whereas the improvement was estimated by symbol error rate (SER) obtained by direct error counting of 2^{20} simulated equiprobable symbols. Also, the transformation is accompanied by the power-dependent phase shift, which, through being small, can be significant for densely packed constellations in cascaded regime. It can be reduced by a single optical phase conjugator (OPC) inserted in the middle of the transmission line. Note, that the amplitude levels in the circular constellation are defined by the regenerative element, therefore the resulted format will have worse performance in a linear transmission than the optimized 256 circular IPM or rectangular QAM. However, in case of cascaded regeneration due to efficient amplitude regeneration the considered constellation outperforms constellations optimal in the linear case. Figure 2 shows constellations at the receiver and the improvement in SER after transmission with SNR=30dB without regenerators (blue, left), with 10 (green, central) and 20 (red, right) regenerators. Though the constellation is suboptimal and SER of 256-QAM is 0.001 for these SNR values, nevertheless it is shown that the proposed regenerative element suppresses amplitude noise effectively. Further optimization of constellation and regenerative parameters as well as suppression of the phase noise will only improve performance. Therefore, we believe that the proposed approach has great potential for proving performance of multi-level signal transmission.

4. Conclusions

We proposed a novel scheme for amplitude regeneration that allows effective regeneration of 9 amplitude levels for 256-symbol constellation. The model enables increase of the number of regenerated amplitude levels.

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