Optics Communications 322 (2014) 114–117

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

On multi-channel operation of phase-preserving 2R amplitude regenerator

Taras I. Lakoba [a,*], Michael Vasilyev [b]

[a] Department of Mathematics and Statistics, University of Vermont, Burlington, VT 05401, United States
[b] Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019, United States

ARTICLE INFO

Article history:
Received 18 November 2013
Received in revised form
5 February 2014
Accepted 7 February 2014
Available online 15 February 2014

Keywords:
Phase-preserving 2R regeneration
Nonlinear amplifying loop mirror
Multi-channel regeneration

ABSTRACT

We analyze multi-channel operation of a phase-preserving amplitude regenerator based on a nonlinear amplifying loop mirror (NALM) with a dispersion-managed nonlinear medium. We show that, under the conditions similar to those of the previously studied multi-channel Mamyshev regenerator, the multi-channel performance of the NALM-based regenerator with phase-encoded signals is considerably worse than that of Mamyshev regenerator with on-off-keying signals. This is explained by a weaker, compared to a timing jitter's, dependence of nonlinear phase jitter on the inter-channel spacing. We show that the multi-channel NALM performance can be significantly improved by using the dispersion map that includes a larger number of fiber sections separated by periodic group-delay devices.

Phase-preserving amplitude regenerators are important for processing phase-encoded (e.g., differential phase-shift keying, or DPSK) signals in long-haul communications [1–11]. Indeed, even though these devices do not directly regenerate the phase, by reducing the amplitude jitter they mitigate the leading transmission impairment of the phase-encoded signals: the rapidly growing phase jitter arising from the amplitude-to-phase noise conversion by self-phase modulation (SPM). One such regenerator scheme, based on a nonlinear amplifying loop mirror (NALM) [1,2,4–6] and shown in Fig. 1(a), is potentially capable of regenerating multiple wavelength-division-multiplexing (WDM) channels, if a specially suited nonlinear medium is used.

In [12] we considered a modification of the NALM-based regenerator introduced in [4–6] that addressed two issues of the original regenerator model: it could operate with pulses having duty ratio common in telecommunications (33–50%), and it had a considerably smaller signal power in the nonlinear medium of the NALM. The latter is a necessary condition for the regenerator to be able to process multiple channels simultaneously. For the same reason, the nonlinear medium considered in [12] was dispersion-managed: it consisted of sections of high-dispersion, highly nonlinear fiber (we used dispersion-compensating fiber, DCF) providing negative dispersion $D=-120$ ps/nm/km, alternated with periodic-group-delay devices (PDGGs), providing positive dispersion [see Fig. 1(b)]. The use of PGDDs has been previously shown to enable WDM operation of a 2R non-phase-preserving regenerator for amplitude-shift-keying (ASK) signals (see [13–15] and references therein). Ref. [12] analyzed the regenerator scheme of Fig. 1 for phase-preserving 2R regeneration of a *single channel*. In what follows we refer, for brevity, to that regenerator as the DPSK regenerator and to the ASK-signal regenerator proposed in [13,14] as the Mamyshev regenerator (after the author of its original single-channel concept introduced in [16]).

In this communication we report on the performance of the DPSK regenerator simultaneously processing *multiple channels* under the conditions similar to those of the multi-channel Mamyshev regenerator. We will show that the multi-channel performance of the DPSK regenerator is considerably worse than that of the Mamyshev regenerator. We will propose an explanation of that and will also demonstrate what modification to its setup can, in principle, improve the DPSK regenerator's performance to a potentially useful level.

Some of the parameters of the DPSK regenerator from [12] are summarized below. The remaining ones can be found in [12]; they will not be referenced in this paper. The nonlinear medium consists of $N_{\text{sections}}=$ six 1.25 km DCF sections separated by PGDDs. The pulse's full width at half maximum is about 50 ps (10 Gb/s signal with 50% duty cycle). The signal is provided a precompensation $\mathcal{D}_{\text{pre}}=-200$ ps/nm and has the average peak power of about $P_{\text{in}}=6.8$ mW before entering the NALM. The word "average" accounts for the fact that input pulses have amplitude jitter. All losses are ignored, as they were ignored in [12]; however, we will comment on this later on. The splitting ratio of the NALM's coupler is $\alpha=0.75$, with 25% of the power propagating in the counterclockwise direction, and the amplifier's gain is $G=20$ dB. Thus, the peak power in the nonlinear medium in the counterclockwise

---

[*] Corresponding author. Tel.: +1 802 656 2610.
E-mail address: tlakoba@uvm.edu (T.I. Lakoba).

http://dx.doi.org/10.1016/j.optcom.2014.02.026
0030-4018

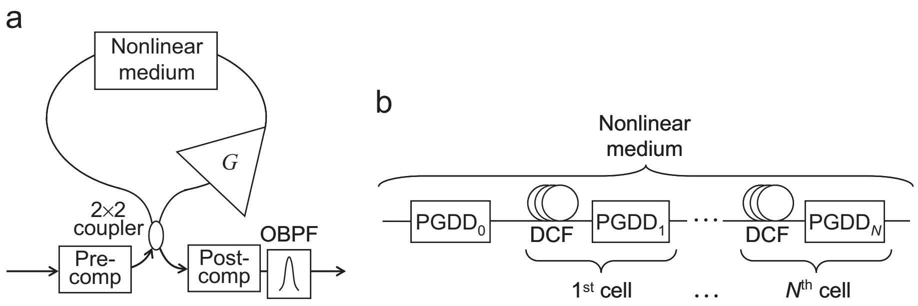

Fig. 1. (a) Schematics of a NALM-based regenerator and (b) details of the nonlinear medium needed for multi-channel operation of the NALM.

direction is about 170 mW, which is about 80% of that in the Mamyshev regenerator employing the same nonlinear medium [14]. In the clockwise direction the power is much smaller, because the clockwise-propagating signal has not passed through the amplifier before entering the nonlinear medium. In [12] we demonstrated that the DPSK regenerator improves the single-channel eye opening (EO, measured with a 10-ps “window”) by 1.1 dB. Below we consider how the account of multiple channels affects this figure.

We consider regeneration of five DPSK channels separated by 200 GHz; thus, the spectral efficiency here is the same as in the previously studied multi-channel Mamyshev regenerator [13,14]. Each simulated channel carries the same pseudo-random bit sequence of 2^7-1 pulses (padded with one ZERO), onto which the same pattern of amplitude jitter is imprinted at the input. This jitter is designed to be $\pm 30\%$ peak-to-average and uniformly distributed within that range. At the input to the NALM (before the precompensating module), the channels had the following bit delays relative to each other:

$$a \cdot T_{\text{bit}} \cdot \{-2.3,\ -1.15,\ 0,\ 1.15,\ 2.3\} + \text{rand}\,(1,5) \cdot T_{\text{bit}}, \qquad (1)$$

where $T_{\text{bit}} = 100$ ps, a is a numerical coefficient (see below), and `rand(1,5)` is a list of five random numbers uniformly distributed between 0 and 1. The channels have no phase jitter at the input. The interchannel bit delays considerably affect the eye opening (EO) of the regenerated signal. (This is similar to the situation in the Mamyshev regenerator, although it occurs for another reason, as we will discuss later on.) Therefore, we ran a simulation for 50 different sets of bit delays, taking $a = 0, 2, 4, \ldots, 98$ in (1), with `rand(1,5)` being different for each value of a. The measure of the regenerator's performance is

$$\text{EO}_{\min} = \min_{\{a\}} \left[\min_{N_{\text{channels}}} (\text{EO}) \right]; \qquad (2)$$

that is, for each run we consider the worst of the five channels and then take the worst result among 50 runs. We have found $\text{EO}_{\min} = -0.4$ dB; thus, in the worst case, the regenerator further degrades (by up to 0.4 dB) some of the channels instead of improving them. (The best of $\min_{N_{\text{channels}}}(\text{EO})$ out of 50 runs is 0.6 dB, i.e., it shows improvement by the regeneration.) As a clarification, let us point out that we have performed this 50-run simulation for several values of parameters $(P_{\text{in}}, \mathcal{D}_{\text{pre}}, \alpha)$ within $\pm 15\%$ of their values which were found to be optimal for a single channel and reported above. We found that while $\mathcal{D}_{\text{pre}} = -200$ ps/nm and α=0.75 remained optimal for the multi-channel case, the input power needed to be lowered to produce better results. The above value $\text{EO}_{\min} = -0.4$ dB was obtained for $P_{\text{in}} = 5.8$ mW, which was found to yield the largest $\text{EO}_{\min}$ in the multi-channel case.

Thus, even though the effective nonlinearity of the DPSK regenerator is less than that of the Mamyshev regenerator [14] and their spectral efficiencies are the same, the multi-channel performance of the former regenerator is considerably worse. Below we address two questions motivated by this fact:

- *Question* 1: Why is this so?, and
- *Question* 2: What modification to the DPSK regenerator can, at least in principle, bring its performance to a potentially useful level?

Our answer to *Question* 1 is that the principal interchannel impairments of ASK and DPSK signals scale differently with the interchannel spacing $\Delta\nu$. For ASK signals, the principal impairment at 10 Gb/s is the timing jitter induced by cross-phase modulation (XPM); it scales as $1/(\Delta\nu)^2$ in both constant-dispersion [17] and dispersion-managed systems, even those including PGDDs [18,19]. As pointed out in [18], this rapid decay of the major transmission impairment with $\Delta\nu$ is the reason why transmission simulations of ASK signals with just a few channels are known to yield practically the same results as when the number of channels is increased. In other words, the main source of the XPM-induced timing jitter is the collisions with the nearest channels, with remote channels contributing much less to this effect.

On the other hand, for phase-encoded signal formats, the degradation comes mainly from the amplitude and phase jitters. The input pulses, by assumption, have amplitude jitter, and it is the regenerator's purpose to reduce it. Therefore, one should look instead at the XPM-induced phase jitter and its subsequent conversion into amplitude jitter by the NALM as the culprits. We will first discuss how this jitter occurs and then will address the issue of its scaling with the interchannel separation.

To begin, we need to review the operational principle of the DPSK regenerator. Recall that at the input to the NALM, the signal u_{in} is split into two, one propagating co-, and the other, counter-clockwise (see Fig. 1(a)):

$$u_{\text{co,in}} = \sqrt{\alpha}\, u_{\text{in}}, \quad u_{\text{cntr,in}} = i\sqrt{1-\alpha}\, u_{\text{in}}. \qquad (3a)$$

As we have discussed above, only the counter-propagating signal, which goes through the amplifier before entering the nonlinear medium, is intense enough to undergo transformation due to an interplay between nonlinearity and dispersion. This transformation affects both the shape of $u_{\text{cntr}}-$pulses (they become narrower and develop wiggles at the “tails”) and their phases. In particular, the amplitude jitter of the input pulses is transferred into phase jitter by self-phase modulation. For the single-channel case and the parameters listed above, we measured the phase jitter of $u_{\text{cntr}}-$pulses before NALM's output to be about 0.35π rad (peak-to-average). Note that this jitter is correlated with the amplitude jitter of $u_{\text{cntr}}-$, and hence also of $u_{\text{co}}-$, pulses; see (3a). Therefore, when those pulses are combined at the output of the NALM,

$$u_{\text{out}} = \sqrt{\alpha}\, u_{\text{co,out}} + i\sqrt{1-\alpha}\, u_{\text{cntr,out}}, \qquad (3b)$$

the jitter in both amplitude and phase of the resulting pulses u_{out} can be minimized by a proper choice of parameters.

In the worst five-channel case reported above, we measured the phase jitter of $u_{\text{cntr}}-$pulses before the output of the NALM to be 0.5π rad (again, peak-to-average), which is the maximum possible measurable value for the two-level phase encoding. This extra jitter of $0.5\pi-0.35\pi=0.15\pi$ leads to a large amplitude jitter in the pulses, u_{out}, at the output of the regenerator. In the aforementioned worst case, we measured the amplitude and phase jitters of u_{out} to be $\pm 42\%$ and $\pm 0.06\pi \approx 0.2$ rad, respectively.

Note that this extra phase jitter of $u_{\text{cntr}}-$pulses in a given channel occurs due to collision with pulses in other channels, but *only when those perturbing pulses have amplitude jitter*. Indeed, if the perturbing pulses all had the same amplitude, then all pulses in the affected channel would have the same XPM-induced phase shift. We have confirmed this by propagating five channels of which only one had amplitude jitter. As predicted, the EO of this channel after regenerator was practically the same (within 0.1 dB) as that in the single-channel case.

These observations also allow us to explain why the interchannel bit delays affect the output amplitude jitter. Suppose a pulse in a given channel (channel 1) has N_{coll} collisions with pulses in another channel (channel 2). Then two pulses in channel 1 separated by at least $2N_{\text{coll}}$ bits “see” completely different sequences of colliding pulses and hence experience uncorrelated XPM-induced phase shifts, because pulses in channel 2 have amplitude jitter. By shifting channel 2 relative to channel 1 (which is what changing the bit delay does), one changes the colliding sequence and hence the resulting XPM-induced phase shift of each pulse in channel 1.

Let us now turn to the issue of how the XPM-induced phase jitter depends on the interchannel frequency separation. Surprisingly, we have been unable to find an analytic expression for that jitter in dispersion-managed systems carrying return-to-zero pulses. In constant-dispersion systems, the classic result [17] predicts that the phase shift after collision of two solitons satisfies:

$$\delta\phi_{\text{coll}} \propto P_{\text{in}}/(D\Delta\nu), \tag{4}$$

where D is the fiber's dispersion. Note the slower decay of $\delta\phi_{\text{coll}}$ than of the timing shift with the interchannel spacing. We believe that in dispersion-managed systems, $\delta\phi_{\text{coll}}$ also scales according to (4). Indeed, during each microcollision, which is a part of a complete collision in a dispersion-managed system [18,19], $\delta\phi_{\text{coll}}$ scales as in (4), and such shifts from all microcollisions have no reason to perfectly cancel out within a complete collision, which would have been the only way for the phase shift to decay with $\Delta\nu$ faster than shown in (4).

Thus, we conclude that it is the amplitude jitter in the neighboring channels that, in combination with the slow decay of the XPM-induced phase shift (4) with channel spacing, must be the culprit in the noticeable degradation of the multi-channel DPSK regenerator's performance compared to the performance of both a single-channel DPSK regenerator and a multi-channel Mamyshev regenerator [14].

We have verified in two ways that the slower decay of the phase shift with $\Delta\nu$ compared to that of the timing shift has played an important role in this degradation. First, for the “worst” set of bit delays (1) for which $\text{EO}_{\min}=-0.4$ dB was found, we have repeated the simulations with $\Delta\nu=800$ GHz instead of 200 GHz. For the Mamyshev regenerator, such an increase in channel spacing improves the performance to almost the single-channel level, whereas for the DPSK regenerator we have found $\text{EO}_{\min}$ to improve to only 0.2 dB. Second, we have repeated simulations for nine instead of five 200-GHz-spaced with several sets of bit delays and observed a performance degradation to $\text{EO}_{\min}=-0.8$ dB. As we have explained above, this would not have occurred for the Mamyshev regenerator, which was shown experimentally to have the numerically predicted performance even with twelve channels [15].

Let us briefly note that we have also run five-channel simulations for a DPSK regenerator with a mismatched coupler in the NALM [20], whose operating power was reported [12] to be about five times below that of the regenerator with the conventional power discussed above. Despite this lower power, we found $\text{EO}_{\min}$ for that regenerator to also fall below 0 dB. At this point, we do not have a convincing explanation of this unexpected fact, because we have only sampled a small fraction of the large parameter space enabled by the mismatched coupler, and a larger-scale optimization would be needed to understand this effect better.

We now address *Question* 2. It is clear that faster interchannel pulse collisions and/or a decrease of power of colliding pulses will lead to a smaller degradation of the multi-channel performance of the DPSK regenerator. Faster collision, for a fixed channel separation, can be achieved only by increasing the (absolute value of) dispersion of the highly nonlinear fiber. This does not appear to be technologically feasible, given that our simulations already use a high-dispersion DCF with $D=-120$ ps/nm/km. The use of a photonic-crystal fiber also appears to be problematic given its relatively high loss for the total length that would be needed to provide enough nonlinearity for regeneration to occur.

The remaining option is to use less intense pulses and increase the length of the nonlinear medium to provide the same total nonlinear phase shift from the SPM. This will result in an increase of the number of PGDDs, because the length of one DCF–PGDD section should be kept approximately constant in order to preserve a value of the dispersion map strength which was found to be optimal for the single-channel operation [12]. Increasing the number of PGDDs will have both a positive and a negative implication. The positive one is a better averaging of XPM phase shifts over many collisions, which will improve the regenerator's performance. The negative one is technological: PGDDs that are commercially available today have relatively high price and noticeable insertion loss (about 3–5 dB) [21,22]. This will necessitate providing additional gain (e.g., Raman) inside the nonlinear medium. However, there are potential alternative solutions that permit fabrication of a large number of PGDDs on a chip [23,24]. Such solutions not only offer lower cost, but also promise much lower losses owing to a better matching between the PGDD waveguides and the small mode size of the DCF. Rapidly advancing fabrication technology of silica-on-silicon, silicon-nitride, and other photonic integrated circuit platforms will make the use of large numbers of PGDDs in a regenerator practical.

To demonstrate that the above method of reducing the input power and simultaneously increasing the nonlinear medium's length does indeed improve the performance of a multi-channel DPSK regenerator, we have repeated our original simulations while making the following modifications. The total length of the nonlinear medium and the number of PGDDs has been increased by a factor of four; i.e., we now have 24 DCF–PGDD sections of the total length 30 km. The input power could then be lowered by about the same factor. In fact, we have kept the NALM's splitting coefficient $\alpha=0.75$ and searched through several values of precompensation $\mathcal{D}_{\text{pre}}$ and input power P_{in}. We found that $\mathcal{D}_{\text{pre}}=-400$ ps/nm and $P_{\text{in}}=1.3$ mW resulted in the optimal performance: For one hundred runs with nine 200-GHz-spaced channels, each carrying a 2^8-1 PRBS (padded with a ZERO), and interchannel bit delays given by a straightforward nine-channel generalization of (1) with $a=0,2,4,\ldots,198$, we obtained $\text{EO}_{\min}=0.4$ dB. The corresponding eye diagram is shown in Fig. 2(b). It should be noted that the regenerated pulses have low phase jitter: see Fig. 2(c). For the reported worst-case channel, this phase jitter is about $0.04\pi \approx 0.13$ rad peak-to-average; in comparison, for a single regenerated channel, it is about $0.03\pi \approx 0.10$ rad.

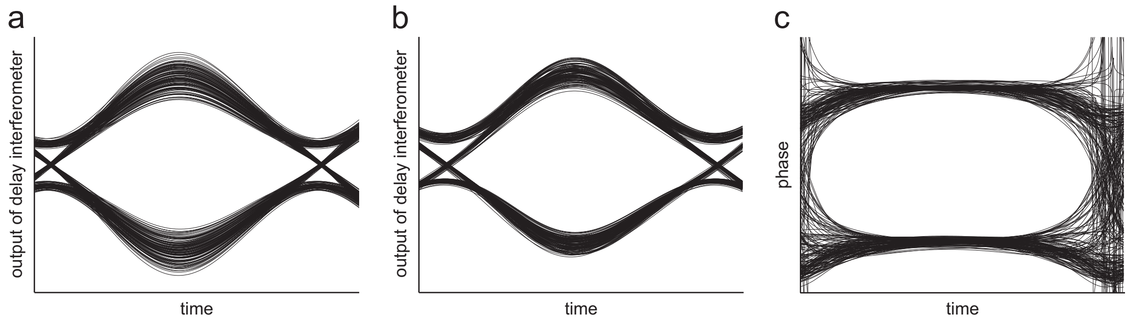

Fig. 2. Electrical eye diagrams at the input (a) and output (b) of the worst-case channel described in the text. (c) Phase eye diagram (i.e., phase plotted versus time) of the output for the same worst channel.

We did not include any loss in our simulations because their purpose was to show that the method we had proposed could in principle improve the regenerator's performance, rather than optimize performance of an actual device. From experimental point of view, it is well understood that, until low-loss PGDDs become commercially available, one would need to reduce the optical power excursion over the length of nonlinear medium as much as possible by compensating the PGDD and DCF losses by Raman amplification, for example.

To summarize, we have shown that, under similar conditions, the multi-channel performance of the NALM-based phase-preserving amplitude regenerator of DPSK signals is considerably worse than that of Mamyshev regenerator with ASK signals. We have explained it by a weaker, compared to a timing jitter's, dependence of nonlinear phase jitter on the inter-channel spacing. We have also demonstrated that by employing more DCF–PGDD sections in the nonlinear medium, one can significantly improve the multi-channel NALM performance and make it potentially useful.

Acknowledgement

This work was supported in part by the NSF Grants ECCS-0925706 and ECCS-0925860.

References

[1] S. Boscolo, S.K. Turitsyn, K.J. Blow, Opt. Fiber Technol. 14 (2008) 299.
[2] C. Stephan, K. Sponsel, G. Onishchukov, B. Schmauss, G. Leuchs, IEEE J. Quantum Electron. 45 (2009) 1336.
[3] M. Matsumoto, IEEE J. Sel. Top. Quantum Electron. 18 (2012) 738.
[4] A.G. Striegler, M. Meissner, K. Cvecek, K. Sponsel, G. Leuchs, B. Schmauss, IEEE Photon. Technol. Lett. 17 (2005) 639.
[5] S. Boscolo, R. Bhamber, S.K. Turitsyn, IEEE J. Quantum Electron. 42 (2006) 619.
[6] K. Cvecek, K. Sponsel, G. Onishchukov, B. Schmauss, G. Leuchs, IEEE Photon. Technol. Lett. 19 (2007) 146.
[7] Q.T. Le, L. Bramerie, H.T. Nguyen, M. Gay, S. Lobo, M. Joindot, J.-L. Oudar, J.-C. Simon, IEEE Photon. Technol. Lett. 22 (2010) 887.
[8] H. Chaouch, E. Parsons, A. Tervonen, M. Mattila, W. Weiershausen, T. von Lerber, S. Honkanen, J.-Y. Yang, A.E. Willner, F. Küppers, Opt. Commun. 284 (2011) 2576.
[9] A. Fragkos, A. Bogris, D. Syvridis, R. Phelan, J. O'Carroll, B. Kelly, J. O'Gorman, Amplitude regeneration of phase encoded signals using injection locking in semiconductor lasers, Optical Fiber Communication Conference (OFC/NFOEC), Los Angeles, CA, 2011, Technical Digest on CD-ROM, Paper OWG1.
[10] C. Porzi, A. Bogoni, G. Contestabile, IEEE Photon. Technol. Lett. 24 (2012) 1597.
[11] B. Zou, Y. Yu, W. Wu, X. Huang, X. Zhang, Opt. Commun. 298–299 (2013) 83.
[12] T.I. Lakoba, J.R. Williams, M. Vasilyev, Opt. Express 19 (2011) 23017.
[13] M. Vasilyev, T.I. Lakoba, Opt. Lett. 30 (2005) 1458.
[14] T.I. Lakoba, M. Vasilyev, Opt. Express 15 (2007) 10061.
[15] P.G. Patki, M. Vasilyev, T.I. Lakoba, Multichannel all-optical regeneration, in: Proceedings of the IEEE Photonics Society Summer Topicals Meeting Series, 2010, pp. 172–173, Paper WC2.2.
[16] P.V. Mamyshev, All-optical regeneration based on self-phase modulation effect, in: Proceedings of the 24th European Conference on Optical Communications (ECOC), Madrid, Spain, 1998, vol. 1, pp. 475–476.
[17] S.P. Novikov, S.V. Manakov, L.P. Pitaevskii, V.E. Zakharov, Theory of Solitons: The Inverse Scattering Method, Springer, New York, 1984. Chapter 1, Sec. 10. The results referenced in this communication can be deduced from the unnumbered equations for Δx_{0i} and $\Delta\varphi_{0i}$ found between Eqs. (11) and (12). One needs to Taylor-expand those formulas in the case where $\mathrm{Re}(\lambda_i)=O(1)$ while $\mathrm{Im}|\lambda_i-\lambda_j|\gg 1$; here $\mathrm{Re}(\lambda_i)$ and $\mathrm{Im}|\lambda_i-\lambda_j|$ correspond to the solitons' amplitudes and frequency separation.
[18] X. Wei, X. Liu, C. Xie, L.F. Mollenauer, Opt. Lett. 28 (2003) 983.
[19] M.J. Ablowitz, C. Ahrens, G. Biondini, S. Chakravarty, A. Docherty, Opt. Lett. 29 (2004) 2354.
[20] T.I. Lakoba, J.R. Williams, M. Vasilyev, Opt. Commun. 285 (2012) 331.
[21] D. Yang, C. Lin, W. Chen, G. Barbarossa, IEEE Photon. Technol. Lett. 16 (2004) 299.
[22] R.L. Lachance, S. Lelievre, Y. Painchaud, 50 and 100 GHz multi-channel tunable chromatic dispersion slope compensator, in: Proceedings of the Optical Fiber Communications Conference (OFC), vol. 1, 2003, pp. 164–165, Paper TuD3.
[23] C.K. Madsen, G. Lenz, A.J. Bruce, M.A. Cappuzzo, L.T. Gomez, R.E. Scotti, IEEE Photon. Technol. Lett. 12 (1999) 1623.
[24] N. Stelmakh, M. Vasilyev, Multiport AWG-based dispersion compensators, in: Proceedings of the IEEE Photonics Society Summer Topicals Meeting Series, 2010, pp. 104–105, Paper WB2.5.