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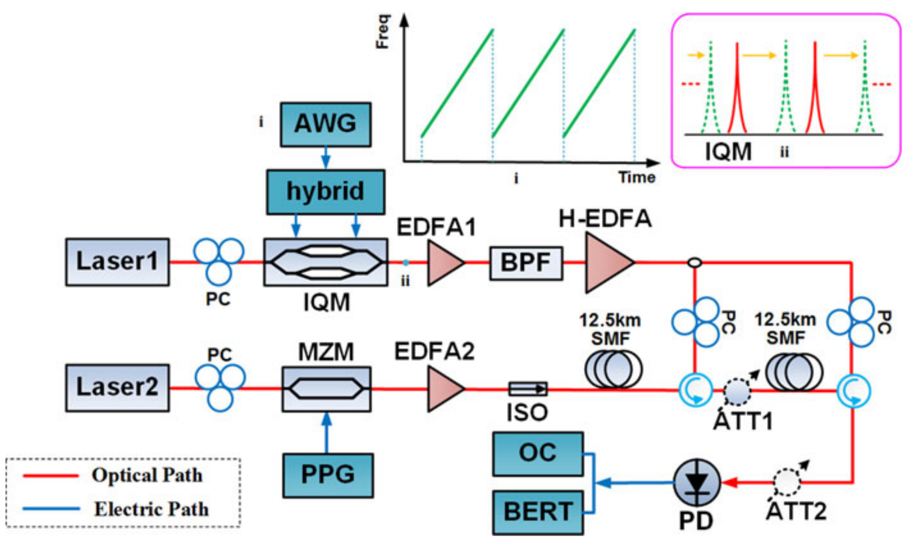

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System Performance Optimization of Frequency-Swept Pump-Based Rectangular Brillouin Optical Filter

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Abstract: In this paper, we realize a series of 2-GHz wide rectangular optical filters based on the stimulated Brillouin scattering (SBS) effect in optical fiber with a frequency-swept pump and gain feedback compensation scheme. The frequency sweep pump period is a key parameter to achieve acceptable signal performance in the frequency-swept pump based SBS gain filter. We evaluate the system performance of the signal, which is fed into the SBS filter based on frequency-swept pump with different sweep periods ranging from 0.1 to 100 μs, in terms of eye diagrams and bit-error rate (BER) after 12.5 and 25 km of fiber transmission, respectively. Both 500-Mb/s and 1-Gb/s on-off-keying (OOK) signals are used for real-time signal quality evaluation. The optimum eye diagram and BER performance are achieved after 25 km transmission under a 1 μs frequency sweep pump period, as well as after 12.5-km transmission under a 0.5 μs sweep period. The experimental results show that the optimal frequency sweep pump period is always around 1/120 of the signal propagation time in the fiber for different transmission length, providing a guideline on the design of the frequency-swept pump based SBS gain filter and its applications.

Index Terms: Rectangular optical filter, microwave photonic filter, frequency sweep, stimulated Brillouin scattering (SBS).

1. Introduction

With the development of processing radiofrequency (RF) signal through optical fiber, the microwave photonic filter (MPF), as an essential component, has many advantages compared to conventional filter, such as low-loss, immunity to electromagnetic interference (EMI), tunability, and reconfigurability [1]–]4]. In recent years, several approaches to generate MPFs have been reported, such as different photonic delay lines [5]–]6], micro-ring resonators [7], and liquid crystal on silicon (LCOS) [8]. An ideal band-pass MPF has a rectangular response consisting of an ultra-flat pass-band, very steep edges and flexible tunability on bandwidth and central wavelength with very high resolution. However, this kind of filter is difficult to be designed based on previous interference or diffraction-based techniques [5]–[8]. MPFs based on stimulated Brillouin scattering (SBS) has become a promising technique due to its extremely high bandwidth resolution of ∼10 MHz [9]–]10]. We have already realized rectangular SBS-based MPF with tunable bandwidth from 50 MHz to 4 GHz with ∼10 MHz tuning resolution in optical fiber [11], [12]. Both multi-tone pump and frequency-swept pump schemes have been used to generate rectangular Brillouin pump spectra, and the gain feedback control scheme has been used to compensate the non-flat frequency response of the used electrical and optical components, therefore achieving rectangular SBS gain spectra. In comparison, frequency-swept pump scheme can achieve better rectangular shape since no four-wave mixing (FWM) effects happen within pump spectra therefore no out-of-band SBS gain is generated. Thus the filter suppression ratio is much higher than the multi-tone pump case [12]. For frequency-swept pump scheme, the period of frequency sweep is a key parameter to achieve both flat spectral response and acceptable signal performance since the signal cannot experience amplification at each point of the fiber for the frequency-swept pump case. It has been highlighted that the frequency sweep period has to be shorter than the signal propagation time in the fiber to guarantee acceptable signal performance [9], [12]; however, there has been no guideline on what the optimal frequency sweep period should be. This is especially important for the short material case, such as chalcogenide fiber or waveguide [13], [14]. Therefore, the optimal sweep period should be studied as a guideline on frequency-swept pump based Brillouin optical filter design.

In this paper, we extensively evaluate the frequency sweep pump period of the swept pump based Brillouin optical filter versus the fiber length as well as signal data rate. We use a 500-Mb/s and 1-Gb/s non-return-to-zero on-off-keying (NRZ-OOK) pseudo-random-bit-sequence (PRBS) data as the input signal of a 2-GHz wide rectangular Brillouin gain filter, and evaluate the eye diagrams and bit-error rate (BER) under different frequency sweep periods ranging from 0.1 μs to 100 μs with the fiber length of 12.5 km and 25 km, respectively. Gain feedback compensation scheme is used to reduce the in-band gain ripple. For fair comparison, the gain bandwidth, gain value and gain ripple are kept almost the same for all cases and we only vary the signal data rate, frequency sweep period and fiber length. The experimental results show the optimal sweep period is mainly related to the fiber length, and it is always around 1/120 of the signal propagation time in the fiber. Thus, we can choose an optimal sweep period according to the fiber length of the frequency-swept pump based SBS filters, providing a guidance for SBS based optical filter design. To the best of our knowledge, this is the first time to verify the influence of frequency sweep period on system performance and signal transmission through the measurement of real-time signal quality. The result is instructive for the research of signal processing based on frequency-swept pump.

2. Rectangular SBS Filter with Different Sweep Pump Period

Firstly, we achieve the rectangular SBS gain filters with different frequency sweep pump periods and fiber lengths. The experimental setup to realize swept pump based rectangular SBS filter is shown in Fig. 1. A distributed feedback (DFB) laser operating at ~1550.57 nm is split into two branches by a 50:50 coupler to generate pump and probe signals in the upper and lower branch respectively. The upper branch is fed into an optical I&Q modulator (IQM) before a polarization controller (PC) which is used to ensure the maximum modulation efficiency. An electrical frequency-swept signal generated by an arbitrary waveform generator (AWG) is modulated by IQM, as shown in the inset (i) of Fig. 1, where the intrinsic bandwidth of SBS gain is 20 MHz. Then an optical carrier-suppressed single-sideband (OCS-SSB) swept signal is obtained after the IQM through adjusting the bias, as shown in the inset (ii) of Fig. 1. After being amplified by a dual-stage high power erbium-doped fiber amplifier (EDFA), where an optical bandpass filter (BPF) is inserted between them to suppress amplified spontaneous emission (ASE) noise, the OCS-SSB signal is then split into two parts equally and send into two SBS gain stages, including a PC, optical circulator and identical 12.5-km long single-mode fiber (SMF) respectively. In each stage, a PC is used to maintain the SBS gain at the maximum value. The dual-stage configuration is used to improve the filter suppression ratio and an optical attenuator (ATT) between the two stages can prevent signal saturation in the second stage therefore effectively increase the filter suppression ratio. In the lower branch, a swept signal with bandwidth ranging from 6 GHz to 12 GHz, which covers the SBS gain region, is produced by an electrical vector network analyzer (EVNA), then is modulated on the CW light utilizing a Mach-Zehnder modulator (MZM) as the probe signal. After suppression of the left sideband by an optical BPF, as shown in the inset (iii) of Fig. 1, the probe light propagates in the two fibers successively

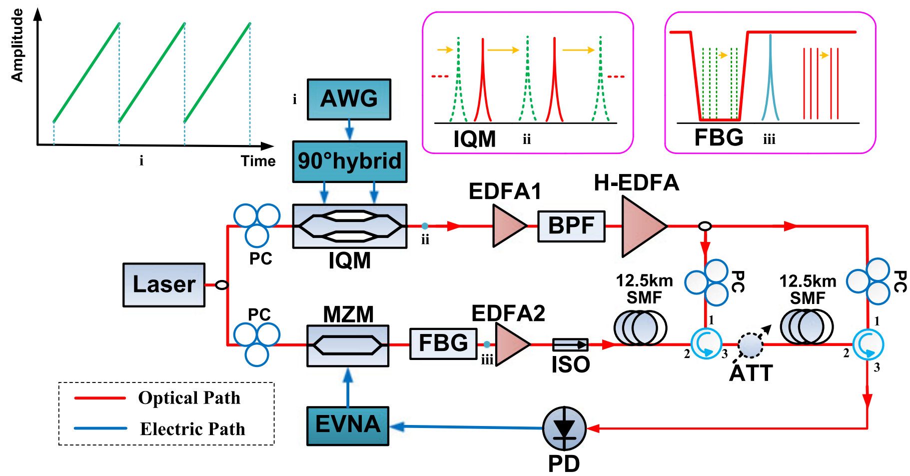

Fig. 1. Experimental setup for achieving rectangular SBS gain filter. PC: polarization controller, AWG: arbitrary waveform generator, IQM: I&Q modulator, EDFA: erbium-doped fiber amplifier, BPF: bandpass filter, H-EDFA: high power erbium-doped fiber amplifier, MZM: Mach-Zehnder modulator, FBG: Fiber Bragg Grating, ISO: isolator, ATT: optical attenuator, PD: photodiode, EVNA: electrical vector network analyzer.

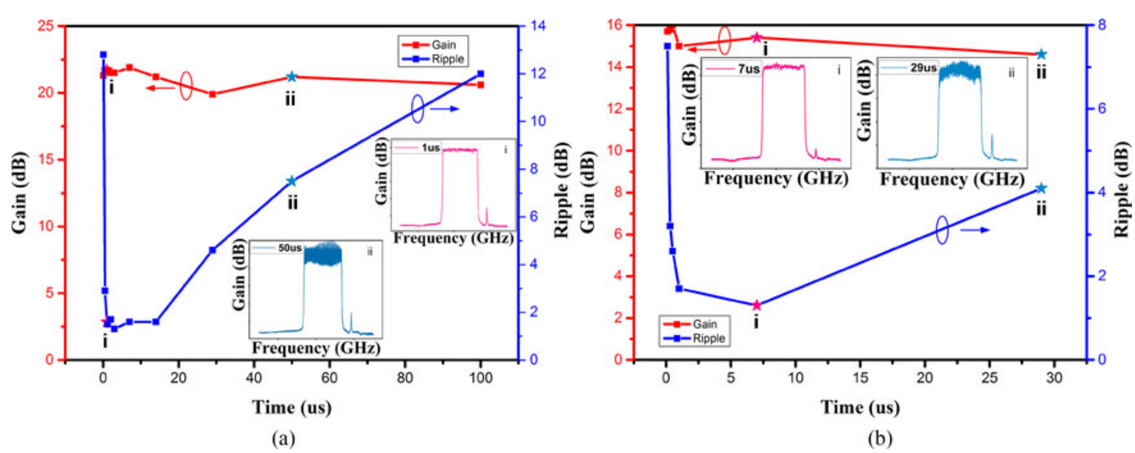

Fig. 2. Gain value and ripple relation with frequency sweep pump period of SBS filter. (a) Fiber length of 25 km. (b) Fiber length of 12.5 km.

and is amplified once it is swept within the SBS gain region. The probe signal is then detected by a photodiode (PD) and sent into the EVNA for frequency analysis. The frequency response is measured by the EVNA and the SBS gain spectra can be obtained by comparing the results with the SBS pump on and off.

We fix the SBS gain bandwidth at 2 GHz in all the following experiments. Then the gain value and gain ripple variation with the frequency sweep period at the same pump power are evaluated as shown in Fig. 2, where the fiber transmission length is 25 km in Fig. 2(a) and 12.5 km in Fig. 2(b), respectively. Note that the higher frequency sidebands in the insets of Fig. 2 are the Brillouin gain of the carrier, which has not been suppressed completely due to the limited driven signal power of the IQM. It can be eliminated by increasing the signal power with high gain electric power amplifier. The red curve represents the variation of the gain values with different frequency sweep pump period, while the blue curve represents the relation between gain ripple and the frequency sweep period. It can be seen that the average gain value almost keeps at the same level for different sweep period, corresponding to similar pump efficiency. The in-band ripple is around 2 dB with sweep period ranging from 1 μs to 15 μs for 25-km fiber length, as shown in the inset (i) of Fig. 2(a). When the sweep period is longer than 0.5 μs, the in-band ripples increase significantly. It may originate from the limitation of feedback compensation algorithm precision with the enormous feedback data. On the other hand, when the sweep period is slower than 15 μs, the SBS gain may be failed to react with the gain from the adjacent frequency, thus introduces much ripple, as shown in the inset (ii) of Fig. 2(a). Therefore, sweep periods that are either too short or too long will result in significant in-band gain ripple. Fig. 2(b) shows the case with the fiber length of 12.5 km and in-band ripple is around 2 dB with sweep period ranging from 1 μs to 7 μs, as shown in the inset (i) of Fig. 2(b). When the frequency sweep period is shorter than 0.5 μs or longer than 7 μs, the SBS gain includes much ripple, as shown in the inset (ii) of Fig. 2(b). The trends of gain and in-band ripple curves are similar to the 25-km fiber case. Undoubtedly the large gain ripple will degrade the signal performance. We then need to evaluate the signal performance relation with different frequency sweep period under the same gain value and minimal gain ripple condition.

3. Frequency Sweep Pump Period Evaluation

For SBS gain filter based on the frequency-swept pump scheme, the sweep period is a key parameter to realize an ideal rectangular filter to amplify signal through the fiber completely. Thus, the frequency sweep period should be short enough to achieve fast response of Brillouin gain, otherwise the signal through the SBS gain filter will be amplified partly. However, short frequency sweep period does not lead to an ideal rectangular SBS filter. With the decreasing of pump frequency sweep period, the feedback compensation algorithm produces much more data to maintain flatness of the SBS filter. Either the data processing or the SBS gain generation process would consume a certain amount of time. Thus, the feedback compensation control can't remain efficiency, leading to invalid feedback control and high in-band ripple. On the other hand, longer sweep period would lead to the failure of the adjacent gain overlay, and also introduce large in-band ripple. Apart from the gain shape, the instantaneous signal quality is a key indicator of the SBS filter performance. Therefore, finding out an optimal sweep period with both minimal gain ripple and best signal quality through experiment is instructive for designing frequency-swept pump based SBS filter. In the following experiments, we will retain the filter shape, including the gain value, gain ripple, and gain bandwidth unchanged for different frequency sweep period and evaluate the signal quality relation with the sweep period for different fiber length and signal data rate.

We have monitored the signal performance amplified by the swept pump based rectangular SBS gain using orthogonal-frequency-division-multiplexing (OFDM) signal in the previous experiment with a specific pump frequency sweep period [15]. However, the OFDM signal is off-line processed, which may not reveal the instantaneous signal quality. Therefore, we use most common-used NRZ-OOK signal, which can truly reflect the system performance, to evaluate the instantaneous signal quality through the SBS gain filter by real-time BER measurement in the following experiments. On the other hand, frequency sweep pump period of 1 μs has been used, which is much shorter than the signal propagation time in the waveguide. However, it is only an experienced value to obtain an acceptable filter performance, and it is not a general guidance to choose an optimal frequency sweep pump period. Therefore, it is important to accurately measure the effect of frequency sweep pump period on the system performance. Based on the 2-GHz rectangular SBS gain filter demonstrated above, the signal is fed into the filter and the signal performances of 500-Mb/s and 1-Gb/s NRZ-OOK PRBS data are evaluated in terms of eye diagrams and BER versus frequency sweep period after different fiber transmission. The experimental setup for the optimal frequency sweep period evaluation is shown as Fig. 3. Different from Fig. 1, two DFB lasers are used respectively and one of them is for generating the SBS filter and the other is for generating test signal. The frequency-swept pump waveforms are retrieved from the AWG where the waveform data are saved after successful feedback compensation. The NRZ-OOK PRBS data are generated by a pulse pattern generator (PPG), and are then launched into the fiber for amplification. The wavelength of two DFB lasers are well tuned to guarantee the signal is within SBS gain region. Although there will be small wavelength

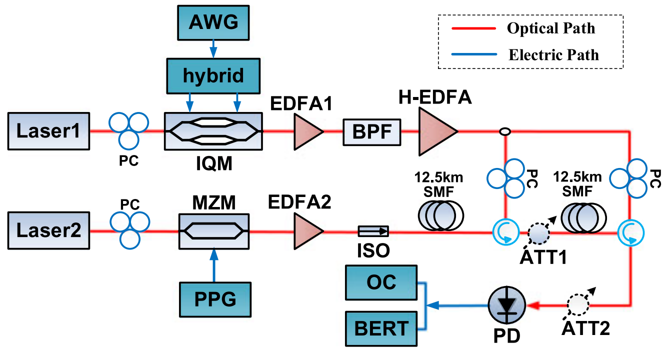

Fig. 3. Experimental setup for optimal frequency sweep pump period evaluation. PC: polarization controller, AWG: arbitrary waveform generator, IQM: I&Q modulator, EDFA: erbium-doped fiber amplifier, BPF: bandpass filter, H-EDFA: high power erbium-doped fiber amplifier, MZM: Mach-Zehnder modulator, PPG: pulse pattern generator, ISO: isolator, ATT: optical attenuator, PD: photodiode, OC: oscilloscope, BERT: bit-error rate tester.

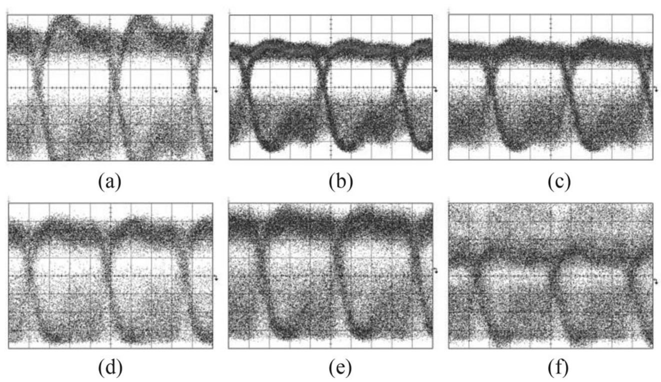

Fig. 4. Eye diagrams with different frequency sweep periods under 25-km fiber case for 500-Mb/s NRZ-OOK signal. (a) 0.5 μs. (b) 1 μs. (c) 2 μs. (d) 7 μs. (e) 14 μs. (f) 29 μs.

drift between the two DFB lasers, 2-GHz gain bandwidth of the rectangular SBS filter is sufficient to cover the signal spectra of the 500-Mb/s and 1-Gb/s NRZ-OOK signals. After passing through the active SBS filter and an optical attenuator (ATT) to adjust the signal power level, the signal is detected by a PD. Using oscilloscope (OC) and bit-error rate tester (BERT), both eye diagrams and BERs are measured to evaluate the signal quality with different pump frequency sweep periods.

The eye diagrams of a 500-Mb/s NRZ-OOK signal passing through the 2-GHz dual-stage rectangular SBS filters with gain around 21 dB and various frequency sweep pump periods of 0.5 μs, 1 μs, 2 μs, 7 μs, 14 μs, and 29 μs are shown in Fig. 4. For 25-km fiber transmission, the signal propagation time is around 120 μs. In the experiment, to obtain higher SBS gain spectrum, as well as to improve the pump power efficiency, small signal, which is lower than 20 dBm, is used for test to prevent gain saturation. Therefore, the test signal performance before SBS gain filter is not good enough and the eye diagram is small. But after amplified by the SBS gain filter, the eye diagram of the test signal is opened, as shown in Fig. 4. It not only evaluates the SBS gain filter performance with different frequency sweep periods but also proves the application of SBS filter for small signal recovery. Note that the amplification noise is at the zero level of the eye diagrams due to an inverted PD, and the eye diagrams are gradually degrading with the increase of frequency sweep period. Fig. 5(a) shows the BER curves with different frequency sweep periods under 25-km transmission and the abscissa of Fig. 5 is the received power of PD. When the sweep period is longer than 15 μs, the significant bit errors may come from the large in-band ripple, as shown in Fig. 2.

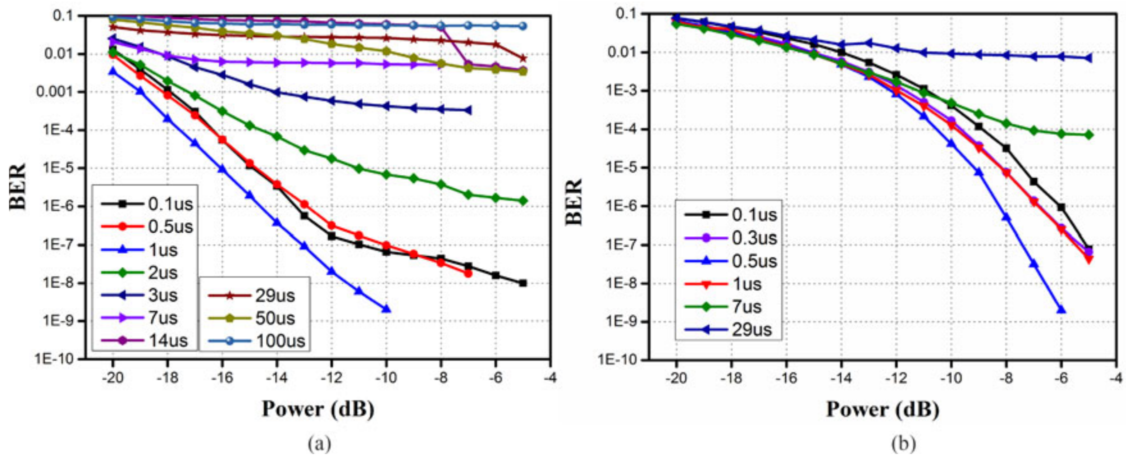

Fig. 5. BER curves with different frequency sweep periods for 500-Mb/s NRZ-OOK signal (a) under the 25-km fiber scheme and (b) under the 12.5 km-fiber scheme.

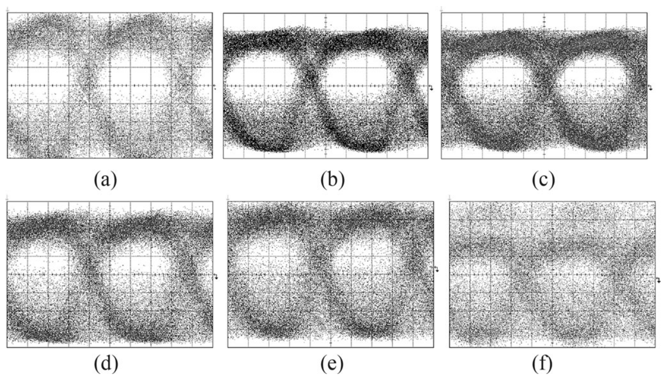

Fig. 6. Eye diagrams with different frequency sweep pump periods under the 25-km fiber scheme for 1-Gb/s NRZ-OOK signal. (a) 0.5 μs. (b) 1 μs. (c) 2 μs. (d) 7 μs. (e) 14 μs. (f) 29 μs.

Meanwhile, for the sweep period from 1 μs to 15 μs, even though the gain ripple is well kept around 2 dB, the BERs performances are completely different, proving the frequency sweep period is extremely important for achieving acceptable signal performance. The optimal BER performance is achieved at the sweep period of 1 μs, corresponding to 1/120 of the signal propagation time in the fiber. If the period is decreased to be shorter than 1 μs, the signal performance will be worse because the increased gain ripple induced by the failure of feedback compensation algorithm. Fig. 5(b) shows the BER curves with different frequency sweep periods under single-stage scheme, corresponding to 12.5-km fiber length and 60-μs signal propagation time. The optimal BER performance is obtained when the sweep period is set to 0.5 μs. It is also corresponding to 1/120 of the signal propagation time in the fiber. Note that for this scheme, the gain ripple at sweep period of 0.5 μs is about 2 dB higher than the 1 μs case, but still it achieves better BER performance. Which proves that the sweep period is indeed a key parameter to determine the signal performance. The above experimental results verify that the optimal sweep period is changing with the fiber length and is about 1/120 of the signal propagation time in fiber.

Furthermore, we verify the signal performance versus optimal frequency sweep pump period at another signal data rate of 1-Gb/s under the 25-km fiber scheme. The measured eye diagrams and BER curves at different frequency sweep periods are shown in Figs. 6 and 7, respectively.

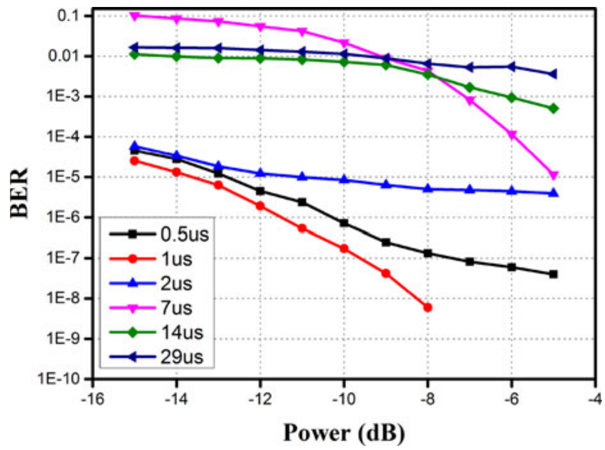

Fig. 7. BER curves with different frequency sweep periods of 1-Gb/s NRZ-OOK signal under the 25-km fiber scheme.

Same as the 500-Mb/s signal case, the optimal BER performance is achieved at the frequency sweep period of 1 μs, corresponding to 1/120 of the signal propagation time in the fiber.

Through the above experimental results, for a given fiber length, the frequency sweep pump period is also a considerable parameter to determine the signal performance for a frequency-swept pump based SBS gain filter, and the optimal frequency sweep period is equal to 1/120 of the signal propagation time in the fiber. Shorter time will increase the feedback compensation algorithm difficulty and induce the high in-band gain ripple, which will also degrade the signal performance. This is the first time to verify the influence of frequency sweep period on system performance and signal transmission through the measurement of real-time signal quality. The result is instructive for the research of signal processing based on swept pump. The SBS gain filter system can be further improved through structure and performance improvement, for example, by changing the modulation method to enhance the filter selectivity, improving structure and instrument to reduce noise and so on. From the results, we can also know the frequency-swept pump based SBS gain filter is only feasible for the long fiber case, and it will be failed for the short fiber cases, such as the chalcogenide fiber or waveguide, where the signal propagation time is in $\sim$ns or even $\sim$ps region, and therefore, it is impossible to sweep the frequency at this time scale.

4. Conclusion

We have realized a series of 2-GHz narrowband rectangular SBS gain filters by changing the frequency sweep pump periods under both 25-km and 12.5 km fiber schemes with the minimum in-band gain ripple, which are obtained using feedback compensation scheme. The optimal frequency sweep period has been evaluated to achieve the best signal performance in terms of eye diagrams and BERs. The experimental results show the best frequency sweep period is mainly related to the transmission time of signal in the optical fiber, and the optimal sweep period is always around 1/120 of the signal propagation time in the fiber. This result can be a general guidance to choose an ideal frequency sweep pump period for designing frequency-swept pump based SBS gain filter and is instructive for all fields which use a frequency-swept pump scheme to generate different Brillouin gain shapes.

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