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Reduction of interchannel interference noise in a two-channel, grating based OCDMA system using a nonlinear optical loop mirror

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Abstract

We show that a nonlinear optical switch can be used to suppress the interchannel noise generated under multi-user operation within a coherent, direct-sequence OCDMA system. By incorporating a simple Nonlinear Optical Loop Mirror (NOLM) within the receiver we demonstrate a 3.6dB power penalty reduction in a two channel, 1.25 Gbit/s, 64-chip, 160 Gchip/s grating based direct sequence OCDMA system. Even greater improvements in system performance were obtained at a data rate of 2.5 Gbit/s, where the noise due to the overlap of adjacent decoded data bits also needs to be suppressed. In both instances the system performance under two-channel operation with nonlinear filtering was shown to be comparable to that achieved under single channel operation using the conventional matched-filter approach.

I. Introduction

Optical pattern generation and recognition are likely to prove important functions in future high-capacity optical networks. These functions are required for example for header recognition in ultra-fast OTDM packet switched networks, and for use within Optical Code Division Multiple Access (OCDMA) systems [1,2]. OCDMA is the optical analogue of the CDMA technique, applied with such success to the field of mobile communications. OCDMA is still in the very earliest stages of technological development but is attractive for a number of reasons including the scope it offers for: networks with high connectivity; more flexible bandwidth usage; asynchronous access; and improved system security.

Superstructured Fibre Bragg Grating (SSFBG) technology represents an attractive means to produce compact, and potentially low-cost components for a wide range of pulse processing applications, including pulse pattern generation and recognition [3,4]. Recently we demonstrated the suitability of SSFBGs for generating, recognising and recoding 64-bit long, 160 Gchip/s, phase-encoded optical pulse sequences [5]. In all of our SSFBG based optical pattern recognition experiments to date we have relied upon the principle of simple matched filtering. Whilst good error free performance has been demonstrated one can envisage incorporating additional nonlinear components within SSFBG based processing schemes to either improve the performance, or to extend the functionality of this technical approach. We recently achieved the first results in this direction by incorporating a fiber based nonlinear optical loop mirror (NOLM) in a single-channel direct sequence-OCDMA receiver, achieving error-free, penalty-free operation [4].

In this paper we report for the first time the use of a nonlinear optical switch to reduce the interchannel interference noise generated under multi-user operation of a SSFBG based OCDMA system. We demonstrate code recognition quality improvement in a two-channel 64-chip, bipolar OCDMA code:decode system using a NOLM within the receiver. The nonlinear switching response of the NOLM is shown to significantly reject interference noise in regions of temporal overlap of the cross-correlation signatures of the individual coded bits, and enhances the pattern recognition contrast achievable using matched filtering alone.

II. Experiment setup and results

Our experimental setup for assessing the performance of a multiple user access system is shown in Fig. 1. Pulses of 2.5ps duration generated using a mode-locked soliton fiber ring laser operating at 10 GHz, were first gated down to a lower repetition frequency, and encoded with pseudorandom data at either 1.25, or 2.5 Gbit/s. The data pulses were then split using a 3dB coupler and fed onto two separate encoder gratings, denoted C1 and C2 respectively, before being recombined into a single fiber using a 3dB coupler. The individual encoding SSFBGs contain phase-coding information within their refractive index profiles as defined by two separate, 'orthogonal', 64-bit Gold codes, such that the impulse responses of the SSFBGs correspond to 64-chip, phase-encoded pulse sequences. Once the data pulses are reflected from gratings C1 and C2 they generate two distinct data streams encoded with either one of the two distinct codes. Note that there was a significant difference in passage time through the system for each of the individually coded data streams so as to remove any possible correlation between the data arriving at the receiver from the two channels. Moreover the relative passage time of the two channels could be fine-tuned to allow anywhere between no and full temporal overlap of the codes at the receiver. Fig. 2(a) shows the spectral reflectivity profile of the two 64-chip, bipolar, phase-shift-keyed Gold sequence SSFBGs C1 and C2. These particular gratings are more fully described in Ref. [5]. The corresponding chip duration is 6.4ps (chip rate = 160 Gchip/s). The coded data pulses thus had a total duration of ~400ps. Interchannel interference noise originates from interference between the essentially singly-peaked and intense pattern recognition signature and the temporally extended, low level cross correlation signatures associated with other codes present within the incident signal beam, which can be confirmed through a comparison of the theoretical auto- and cross-correlation traces between the two codes as shown in Fig. 2(b).

The two distinct data channels were then fed to a single decode grating (C1*) designed to provide matched filter operation to grating C1. The reflection of data pulses encoded with C1, from C1*, thus results in the formation of a short chip-length long autocorrelation pulse on a broad ~800ps long, low level pedestal. This short pulse can then be used to detect a code recognition signature. No such short pulse is generated when pulses encoded using C2 are reflected from the grating due to the particular properties of Gold code sequences. The output from decoder grating C1* could either be detected and characterized directly, or passed through a NOLM before characterization. The NOLM was made from a 70:30 coupler and 6.6km of dispersion shifted fiber (DSF), and was designed to provide both a high switching efficiency and pulse compression. The NOLM serves to remove both the low-level pedestal associated with the presence of the second channel, and the finite background on the decoded pulses, that are obtained by simple matched filtering, resulting in improved system performance. The soliton order inside the NOLM is N= ~3 and the soliton period is 6km (assuming a pulse of the chip duration) [6]. Erbium doped fiber amplifiers (EDFA) optimized for low-noise operation at 1558nm (the operating wavelength) were incorporated within system at appropriate positions to compensate for the loss of various elements such as the transmission line, optical circulators, and couplers. Note that in order to obtain optimal performance of the NOLM peak power of the signal needs to be maintained. Therefore in any practical system, if the total number of channels into the power amplifier was to be changed it would be necessary to change the average output power of the amplifier in order to maintain the optimal peak power.

We performed system tests at the data repetition rates of 1.25Gbit/s and 2.5Gbit/s. The pulses in each channel were set to fully overlap temporally at the detector so as to maximize the impact of interchannel interference. As can be seen comparing the eye diagrams in Fig. 3(a) and (b) the temporal overlap of the two orthogonal codes results in severe interference noise at the receiver without the NOLM in place. However, as can be seen in Fig. 3(c) the quality of the eye opening is drastically improved by nonlinear filtering of the matched filtered signal, resulting in a substantial improvement in the BER performance of the coding:decoding process. The measured BER plots are summarized in Fig. 4. For a data rate of 1.25 Gbit/s error-free operation with a 3.6dB power penalty reduction relative to simple matched filtering alone was obtained through the use of the NOLM. The residual power penalty of ~1.6dB is comparable to that achieved for single channel operation without the NOLM [4]. We believe the penalty in the two channel experiments to be due primarily to the contribution to the received average power made by imperfect suppression of the second ('orthogonal') channel. The benefits of using the NOLM at the higher data rate of 2.5 Gbit/s are even more manifest. In this instance it was not possible to get error free operation without the use of the NOLM. The power penalty relative to the back to back in this instance was 2.8dB, and which again was similar to that obtained for conventional single channel operation at this data rate. Note that at a data rate of 2.5 Gbit/s the individual pattern recognition signatures which each have a length of ~800ps overlap, providing an additional element of intereference noise, hence the slightly increased power penalty relative to the 1.25 Gbit/s case in which no such overlap occurs.

Finally, in Fig.5 we plot the results of SHG autocorrelation measurements of the pattern recognition pulse both before and after self-switching by the NOLM. The pedestal rejection and pulse reshaping effects are seen to be significant. The pulse width after the NOLM is about the same as that of the input pulses derived from the laser which is significant if additional reprocessing of the bit, e.g. recoding [5], is required.

III. Conclusion

We have experimentally demonstrated that the performance of multi-user OCDMA systems can be significantly enhanced through the addition of a simple nonlinear optical switch at the receiver to reject both inter-channel and intra-channel coherence noise. Error free performance can be more reliably obtained with a considerable power penalty reduction, moreover cleaner, shorter pattern recognition signatures are obtained. This latter fact is important if further optical processing of the data should be required. In our experiments to date we used a fiber based NOLM however semiconductor based nonlinear devices should offer similar system benefits.

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Figure captions

Figure 1. Experimental setup for a two-channel 64-chip, 160Gchip/s grating based OCDMA code:decode system.

Figure 2. (a) Spectral profile of SSFBGs for a 64-chip bipolar phase shift keyed Gold sequence corresponding to two codes (C1 and C2) used in our experiment, (b) theoretical waveforms of auto- (C1:C1*) and cross-correlation (C2:C1*) between the two codes prior to the NOLM.

Figure 3. Eye diagrams at 2.5Gbit/s. (a) Back-to-back (b) After matched filtering only (c) After self-switching by the NOLM.

Figure 4. BER versus received optical power for 2-channel operation at 1.25Gbit/s and 2.5Gbit/s.

Figure 5. SHG autocorrelation traces of the central auto-correlation spike of the decoded signal; solid line: after matched filtering (C1:C1* + C2:C1*), dashed line: after subsequent nonlinear switching by the NOLM. The data rate is 2.5Gbit/s.

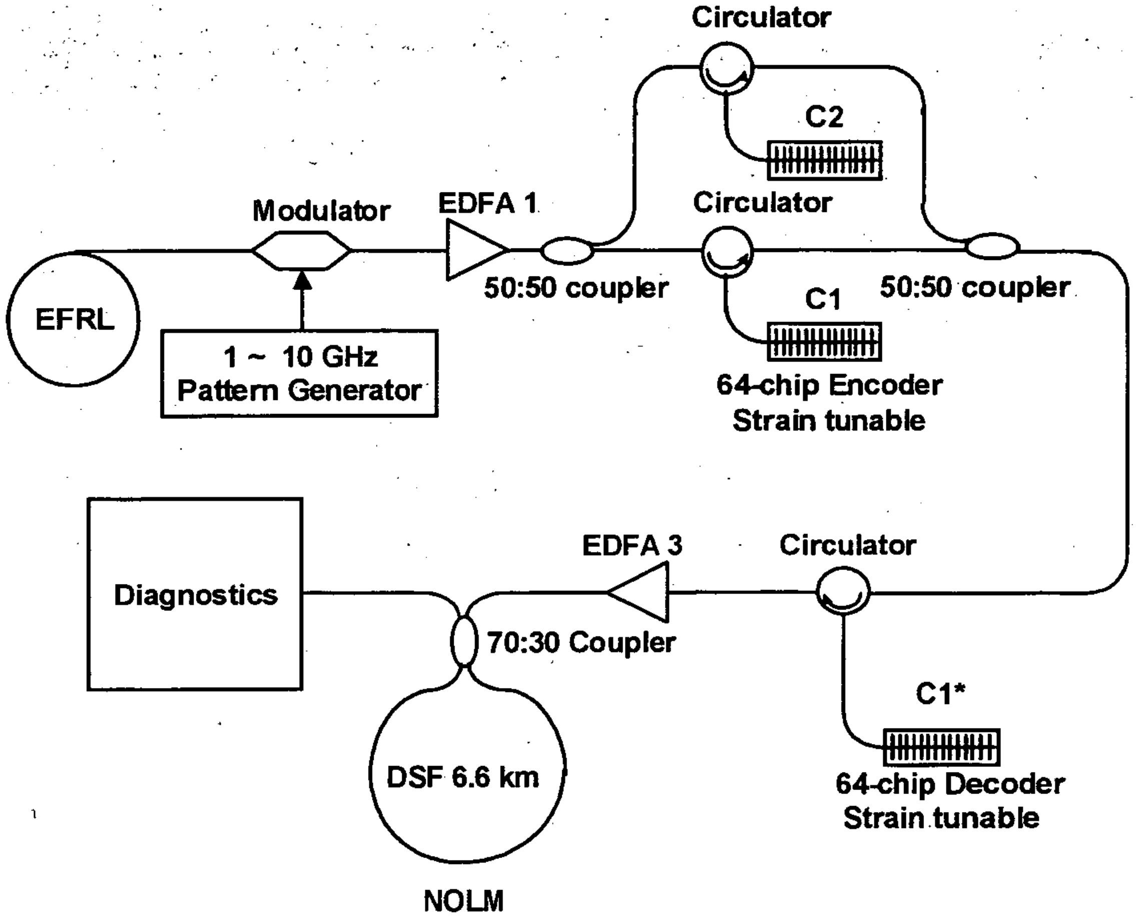
Circulator
C2
Modulator
EDFA 1
Circulator
EFRL
50:50 coupler
C1
50:50 coupler
1 ~ 10 GHz
Pattern Generator
64-chip Encoder
Strain tunable
Diagnostics
EDFA 3
Circulator
70:30 Coupler
C1*
DSF 6.6 km
64-chip Decoder
Strain tunable
NOLM

Figure 1

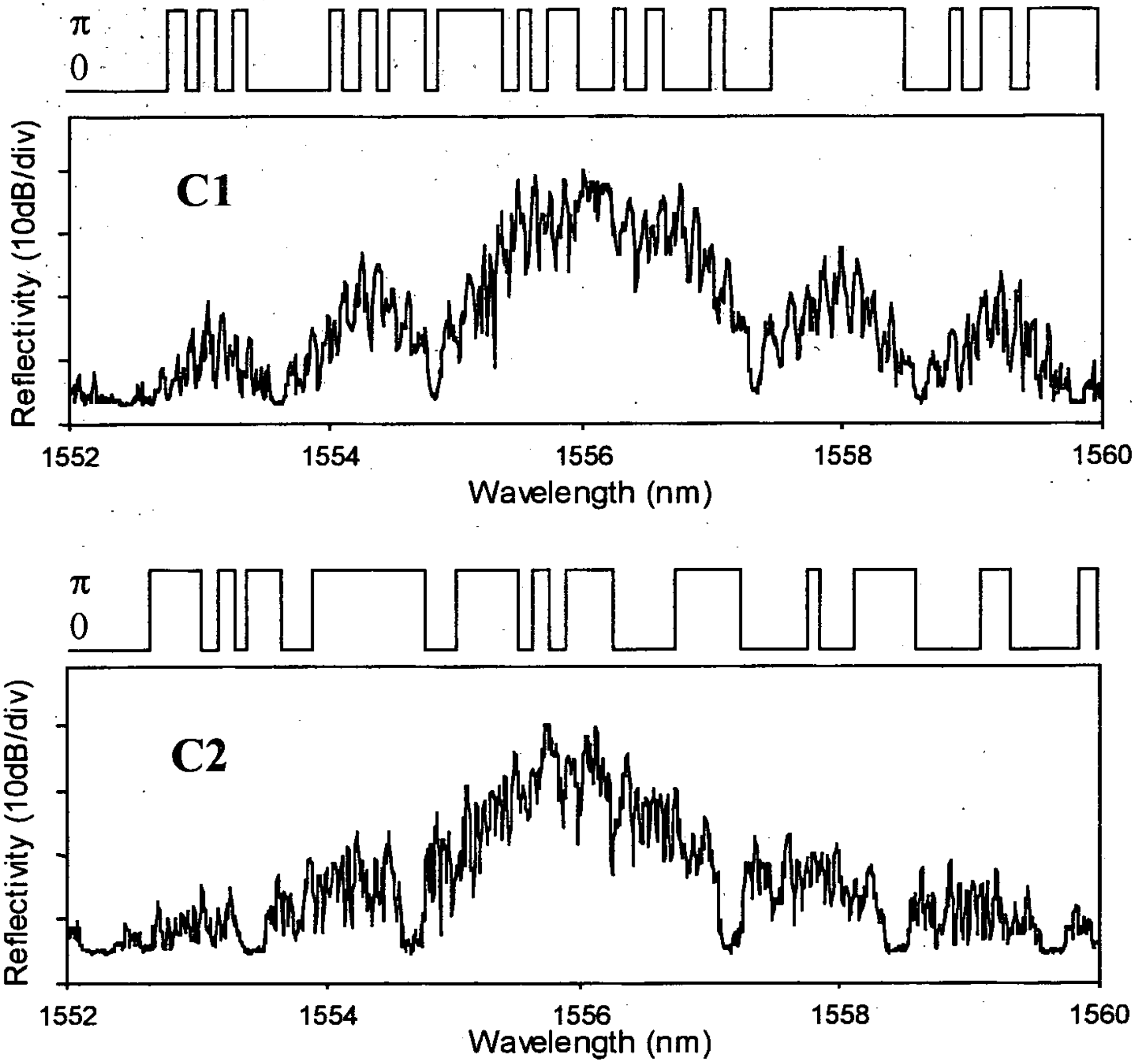
π
0
C1
Reflectivity (10dB/div)
1552
1554
1556
1558
1560
Wavelength (nm)
π
0
C2
Reflectivity (10dB/div)
1552
1554
1556
1558
1560
Wavelength (nm)

Figure 2(a)

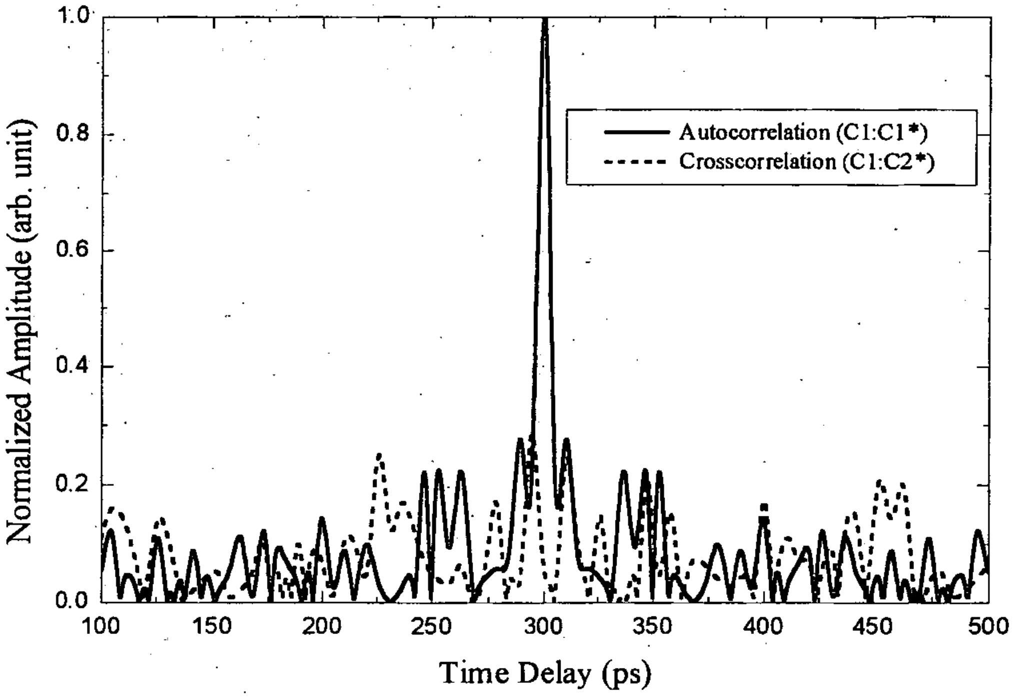
1.0
0.8
0.6
0.4
0.2
0.0
Normalized Amplitude (arb. unit)
100
150
200
250
300
350
400
450
500
Time Delay (ps)
Autocorrelation (C1:C1*)
Crosscorrelation (C1:C2*)

Figure 2(b)

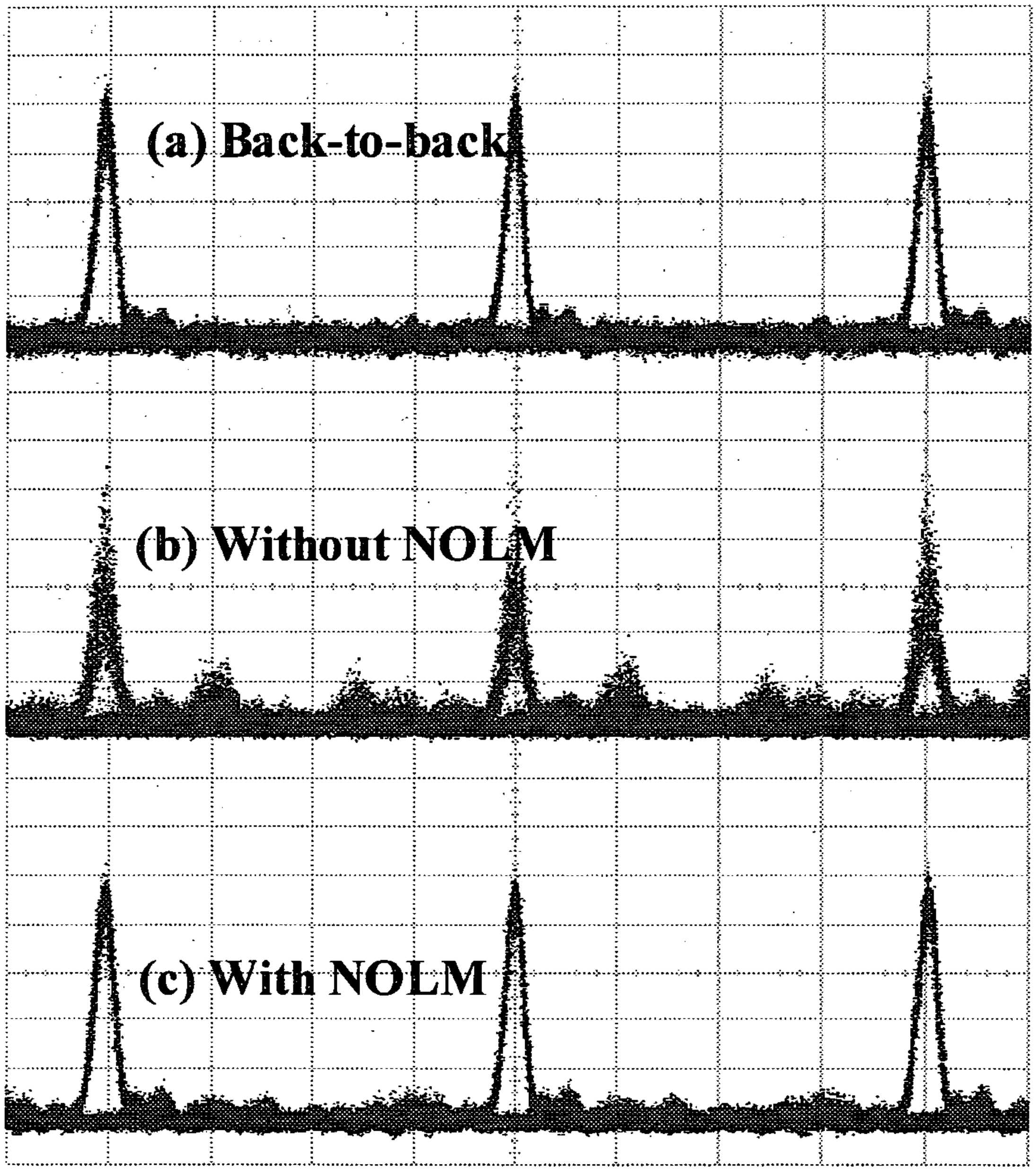

Figure 3

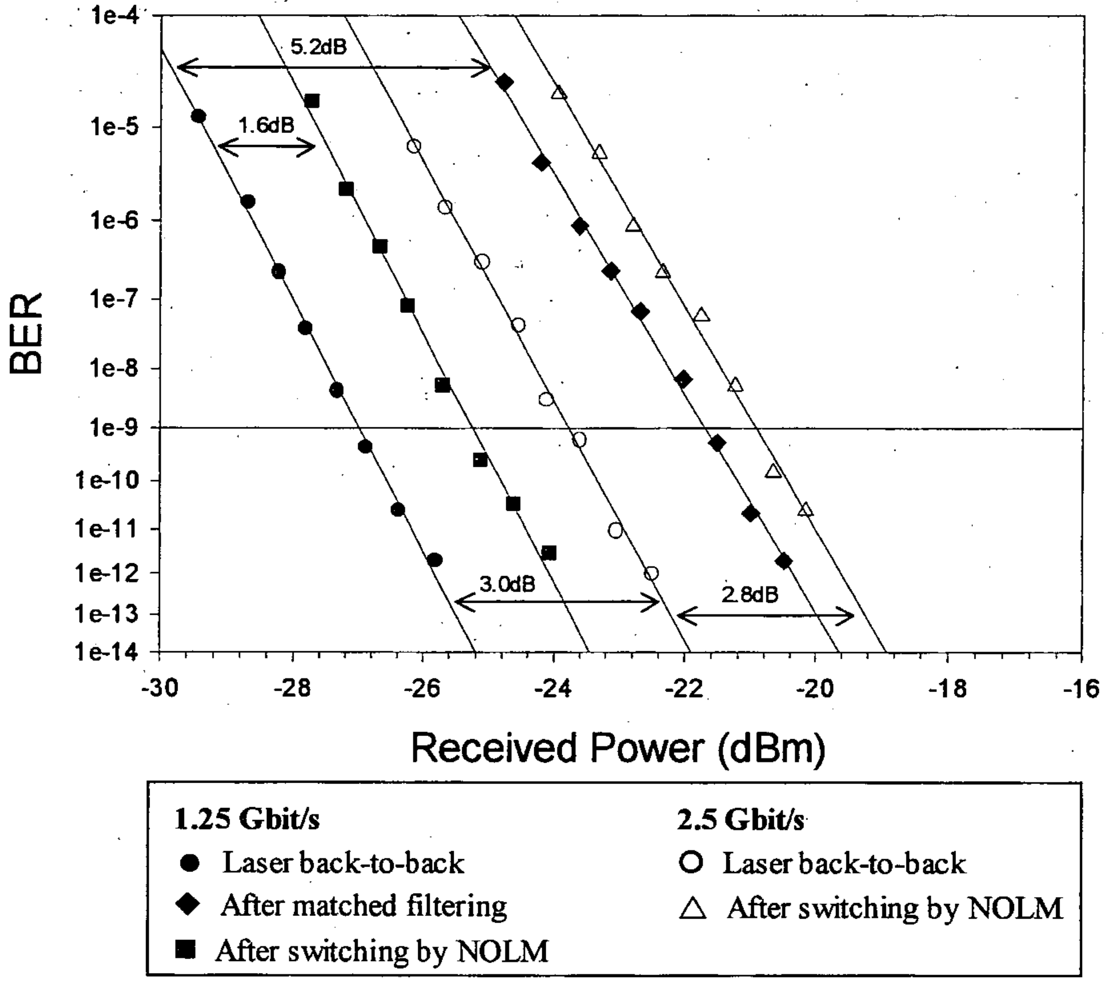
BER
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1e-10
1e-11
1e-12
1e-13
1e-14
-30
-28
-26
-24
-22
-20
-18
-16
Received Power (dBm)
5.2dB
1.6dB
3.0dB
2.8dB
1.25 Gbit/s
● Laser back-to-back
◆ After matched filtering
■ After switching by NOLM
2.5 Gbit/s
○ Laser back-to-back
△ After switching by NOLM

Figure 4

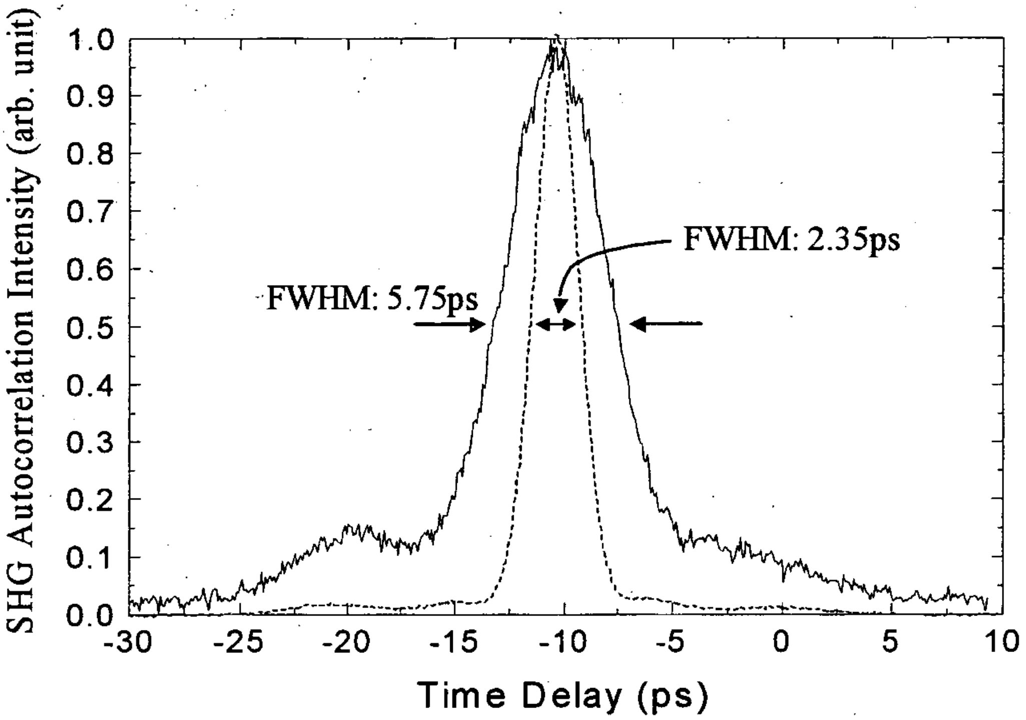
SHG Autocorrelation Intensity (arb. unit)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Time Delay (ps)
FWHM: 5.75ps
FWHM: 2.35ps

Figure 5