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Cascadability of Uniform Fibre Bragg Grating for 40 Gbit/s RZ-OOK to NRZ-OOK Conversion

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ABSTRACT

The cascadability of uniform fibre Bragg grating for 40 Gbit/s return to zero on-off keying to non-return to zero on-off keying format conversion has been shown using OptSim simulation program. The main idea of this approach is use of specially designed uniform fibre Bragg grating with appropriate transfer function for shaping of 40 Gbit/s return to zero on-off keying optical spectrum. Error free performance is achieved after four cascades of uniform fibre Bragg grating with different reflectivity values.

Keywords: All-optical Devices; Fibre Bragg Grating; Fibre Optic Transmission Systems; Format Conversion; Intensity Modulation; Optical Signal Processing

1. Introduction

In last year's photonic technologies for optical transmission have gained great breakthrough because of high demand for bandwidth and need to reduce costs per every transmitted bit [1,2]. To overcome the emerging challenges various optical modulation formats have been utilized in optical transmission depending on the bit rate, transmission distance and media [3].

Historical circumstances have made on-off keying (OOK) in both non-return to zero (NRZ) and return to zero (RZ) in the modulation format of choice for the most of optical transmission systems [3]. Optical modulation format NRZ-OOK is simplest in generation. The Mach Zender modulator (MZM) is biased at 50% of transmission and driven from minimum to maximum. NRZ-OOK modulation format is more spectrally efficient comparing to RZ-OOK and thus is appropriate for metro and access transmission systems because of rather short span lengths and lower bit-rates [1,3]. In turn the RZ pulse fills a part of the bit period which can have three different types of duty cycle: 33%, 50% and 67%. Shorter pulses results in broad spectrum which is clear from properties of the Fourier transform. This is the main drawback of RZ-modulated signals resulting in a reduced tolerance to chromatic dispersion and a smaller spectral efficiency. Still, RZ-OOK format is preferred in transport optical transmission systems thanks to superior tolerance to nonlinear optical effects (NOE), inter-symbol interference (ISI) and polarization mode dispersion (PMD) [3, 4]. Interconnections among transport, metro and access networks are necessary because of different modulation formats in use. Optical-electrical and electrical-optical conversion degrades system efficiency. This is mainly related to increase of time and cost. Therefore it is important to perform all-optical signal processing [1]. This will lead to increase of systems overall efficiency. One of the functionalities of all-optical signal processing is modulation format conversion in optical domain. It will be demanded at the gateways to ensure transparent and efficient interconnection especially for future ubiquitous transparent optical networks.

Different approaches have been worked out for all-optical format conversion. One part of this conversion is related to nonlinear signal processing: semiconductor optical amplifier (SOA)/distributed feedback laser (DFB-LD) [5], SOA-loop-mirror [6], SOA/fibre Bragg grating (FBG) [7], nonlinear optical loop mirror (NOLM) and four-wave mixing (FWM) [8]. Other part is related to linear optical signal processing: specially designed silicon mirroring resonators (MRR) have been used for modulation format conversion [9,10]. The main idea of this approach is use of optimized MRR with appropriate transfer function for shaping of input optical spectrum. Different approach could be based on uniform FBG [11]. In this paper cascadability of uniform fibre Bragg grating for 40 Gbit/s RZ-OOK to NRZ-OOK conversion has been shown using OptSim simulation program.

2. Simulation Method and Model

The OptSim 5.2 simulation program is software tool for the design and simulation of optical communication systems at the signal propagation level. It was applied for demonstration of 40 Gbit/s RZ-OOK to NRZ-OOK format conversion and assessment of cascadability of uniform FBG impact on conversions efficiency. For uniform FBG transfer function calculation Bragg Grating Filters Synthesis (BGFS) 2.6 simulation program was used. The main results of this paper are obtained with two different simulation tools: for physical layer simulation of optical transmission systems and other for synthesis of physical components transfer function depending on different parameters. Calculation method of simulation program OptSim 5.2 solves set of complex differential equations and takes into consideration linear and nonlinear impairments on electromagnetic signal propagation in optical and electrical components of transmission system.

In this research the time domain split step (TDSS) method was used which despite its complexity grants a precise outcome of simulation. This calculation method is used in all commercial simulation tools to perform the calculation of the electromagnetic signal propagation equation in optical fibre:

$$\frac{\partial A(t,z)}{\partial z} = \{L + N\} A(t,z) \quad (1)$$

A (t, z) represents the optical field, L is the linear operator which stands for linear impairments and N is the nonlinear operator which is responsible for nonlinear impairments. The equation (1) is calculated over small spans of fibre by including either linear or nonlinear operator. For instance, on the first span only L is considered, on the second span only N operator and so on [12].

The BGFS 2.6 simulation program was used to obtain FBG transfer function. Transfer matrix method is employed in BGFS 2.6 simulation program to simulate different configurations of FBG filters. It is applied to solve the coupled mode equations and to obtain the spectral response of the FBG filter. The transfer function was for reflection spectra of FBG filter. The FBG parameters were optimized by altering the length of grating and reflectivity parameter. Two different transfer functions of FBG filter reflection spectra were synthesized with uniform apodization profile and 60% and 97.5% reflectivity values. In **Figure 1** and **Figure 2** uniform FBG filter reflection spectrums with 97.5% and 60% reflectivity are shown accordingly.

Us it is noticed two simulation programs were used in simulations. In BGFS 2.6 simulation program calculated reflection spectra of FBG filter was recorded in the data file. After simple mathematical calculations compatible data file format were created for OptSim 5.2 simulation program. User defined optical filter block was used for building of 40 Gbit/s RZ-OOK to NRZ-OOK format converter based on uniform FBG. The synthesis of the user defined optical filter is based on the Overlap and Add algorithm [13]. At first the data points are interpolated so to obtain a continuous transfer function. The algorithms developed to implement user defined filter component are very accurate and the transfer function is synthesized. Then it is applied for investigation of uniform FBG filter cascadability impact on format conversion.

3. Results and Discussion

The simulation setup for investigating of the uniform FBG filter cascadability impact on 40 Gbit/s RZ-OOK to NRZ-OOK format conversion is illustrated in **Figure 3**. The setup consists of three parts: optical transmitter,

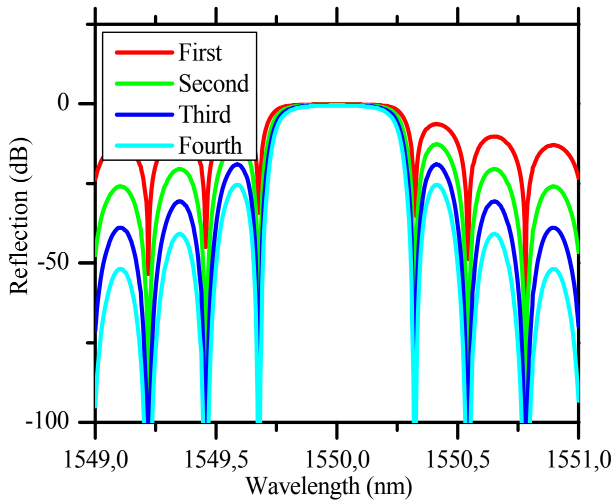

Figure 1. Amplitude transfer function of uniform FBG optical filter reflection spectra with 97.5% reflectivity after different number of cascades shown in inset.

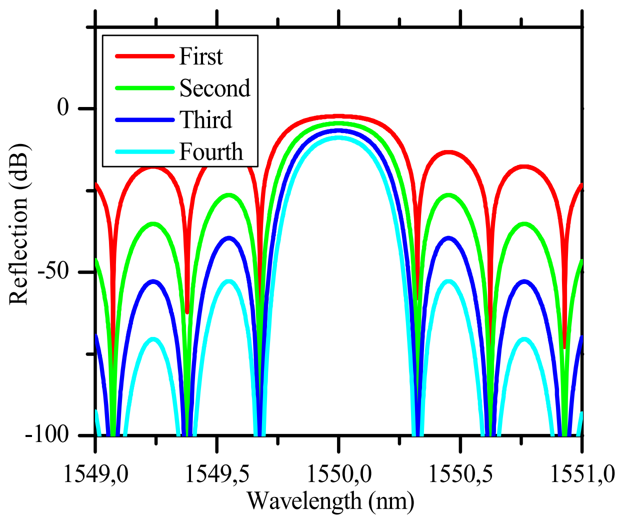

Figure 2. Amplitude transfer function of uniform FBG optical filter reflection spectra with 60% reflectivity after different number of cascades shown in inset.

format converter in cascade configuration and preamplified optical receiver. The optical transmitter for 40 Gbit/s RZ- OOK optical signal generations consists of two $LiNbO_3$ MZMs and continuous wave (CW) light laser. The first MZM was used as a pulse carver driven by a half clock, while the second one was driven by a 40 Gbit/s pseudo random binary sequence (PRBS) with a pattern length of 2^{31}-1. The optical signal was then coupled into the optical format converter which consists of uniform FBG filter and the three port optical circulator. In this investigation four optical format converters were used to see the impact of cascadability on format conversion efficiency. These converters were connected with optical circulators in cascade by connecting third fort of first circulator with first port of next. After each converter 40 Gbit/s NRZ-OOK optical signal was detected in a preamplified receiver. This receiver consists of erbium doped fibre amplifier (EDFA), 100 GHz Gaussian optical band pass filter (OBPF), 45-GHz photodiode, electrical low pass filter (ELPF), optical spectrum analyser (OSA), electrical scope and bit error rate (BER) tester.

Figure 4 shows the power spectrum density (PSD) of the input 33% RZ-OOK, converted NRZ-OOK after different number of uniform FBG with 97.5% reflectivity cascades and generated NRZ-OOK. **Figure 5** shows bit error rate (BER) as a function of received power for the input 33% RZ-OOK and converted NRZ-OOK after different number of uniform FBG with 97.5% reflectivity cascades. Insets: eye diagrams of back to back 33% RZ-OOK signal and converted NRZ-OOK signals. In this case uniform FBG with 97.5% reflectivity was applied for the conversion of signal formats. Increased reflectiveity for uniform FBG leads to lower insertion loss of the device and flat top of the pass band (see **Figure 1**). Accumulation of insertion loss is lower and full width half maximum (FWHM) bandwidth reduction effect is also reduced while filters are cascaded. Due to imperfections of the employed uniform FBG: (the side lobe minimum values are not matched to tones of RZ-OOK signal zeros and pass band shape is not optimized) the RZ-OOK to

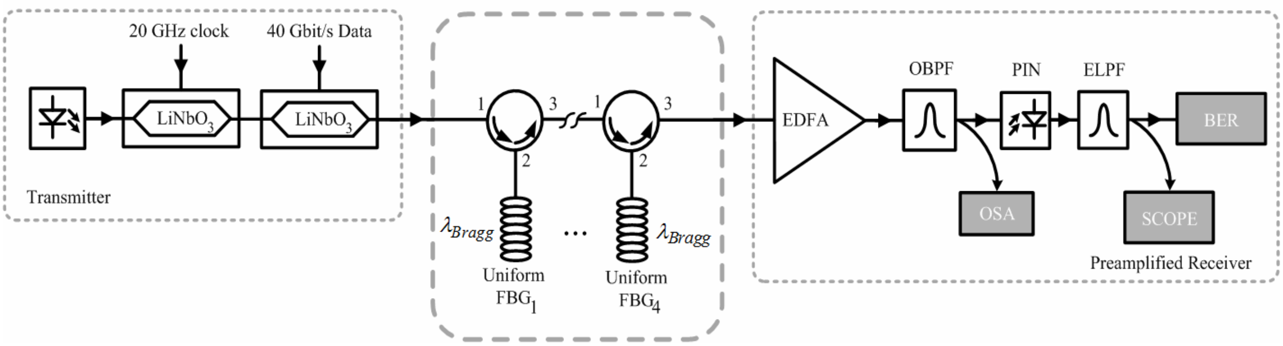

Figure 3. Setup for investigating of the uniform FBG filter cascadability impact on 40 Gbit/s RZ-OOK to NRZ-OOK format conversion.

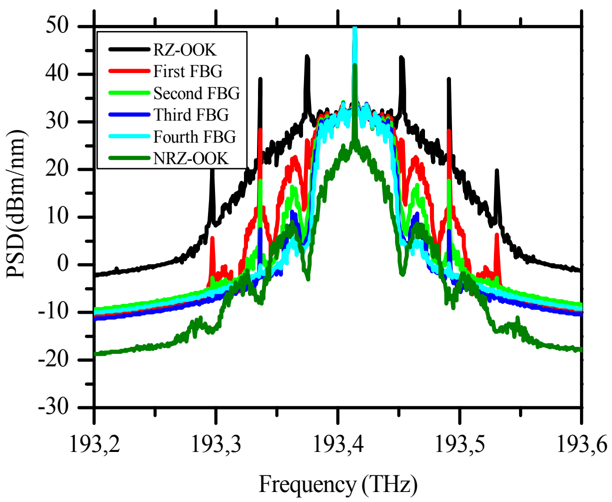

Figure 4. Power spectrum density of the input 33% RZ-OOK converted NRZ-OOK after different number of uniform FBG with 97.5% reflectivity cascades and generated NRZ-OOK. Details are shown in inset.

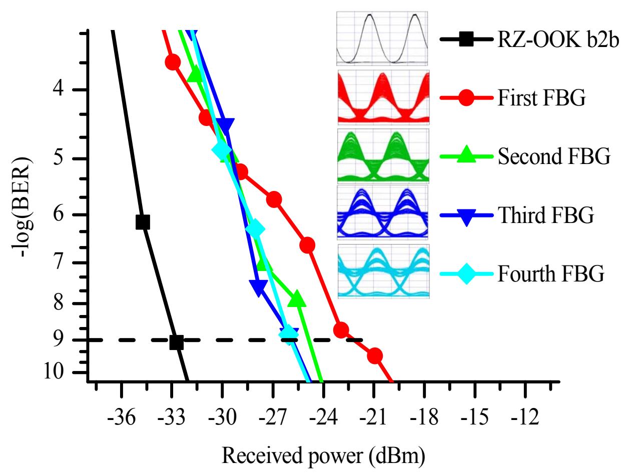

Figure 5. BER as a function of received power for the input 33% RZ-OOK and converted NRZ-OOK after different number of uniform FBG with 97.5% reflectivity cascades. Insets: eye diagrams of back to back 33% RZ-OOK signal and converted NRZ-OOK signals.

NRZ-OOK conversion is not successful. Adding more filters in cascade leads to better BER performance. After third and fourth cascade the eye diagrams shows partial format conversion, but with large amount of amplitude ripples. These ripples could be reduced by adding additional Gaussian band pass filter. Therefore this leads to finding that reflectivity of uniform FBG must not be high. This also leads to drawback which is related to increased insertion loss value.

To obtain more convincing results the additional simulations was carried out with device which has lower reflectivity and less imperfections for transfer function. **Figure 6** shows the power spectrum density (PSD) of the input 33% RZ-OOK, converted NRZ-OOK after different number of uniform FBG with 60% reflectivity cascades and generated NRZ-OOK. **Figure 7** shows bit error rate (BER) as a function of received power for the input 33% RZ-OOK and converted NRZ-OOK after different number of uniform FBG with 60% reflectivity cascades. Insets: eye diagrams of back to back 33% RZ- OOK signal and converted NRZ-OOK signals. As one can see from **Figure 2** uniform FBG with 60% reflectivity has not so flat top at the pass band. After number of cascades this pass band shape tends to be Gaussian like. Also the change in FWHM bandwidth have been observed due to the fact, that cascading of band pass filters leads to usable bandwidth reduction. In the case of RZ-OOK to NRZ-OOK format conversion these properties gives some benefits and limitations. Main contribution from the cascading of uniform FBG with 60% reflectivity could be seen in **Figure 7** eye diagrams for converted 40 Gbit/s NRZ-OOK optical signals. After first filter eye diagram (red colour) has amplitude ripples due to imperfections in filter pass band shape. Still the eye diagram opening is rather high to give error free performance. After adding more uniform FBG filters with 60% reflectivity the eye diagrams were with less amplitude ripples and with better BER performance. This trend was observed till third number of cascade and mainly is caused due to Gaussian like pass band shape which arises from cascading of the filter. However at the fourth number of cascade the effect of FWHM bandwidth reduction leads to over filtering of the converted NRZ-OOK signal and decreased BER performance.

Figure 8 shows the power penalty (at BER = 10^{-9}) induced by cascading of a uniform FBG versus number of cascades for uniform FBG with 60% and 97.5% reflectivity. As it can be seen from the results obtained from BER performance for both 40 Gbit/s RZ-OOK to NRZ-OOK cascaded converters that power penalty decreases with the number of cascades. In the case of uniform FBG with 60% reflectivity minimum point of power penalty is achieved after third cascade and after more cascades it increases significantly due to optical signal over filtering.

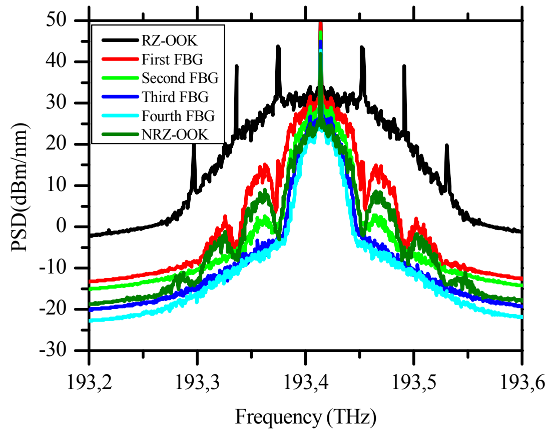

Figure 6. Power spectrum density of the input 33% RZ-OOK converted NRZ-OOK after different number of uniform FBG with 60% reflectivity cascades and generated NRZ-OOK. Details are shown in inset.

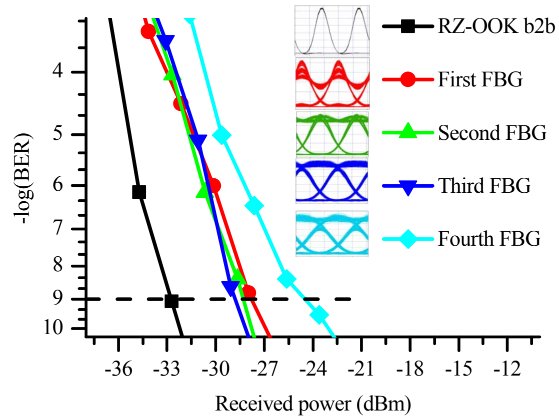

Figure 7. BER as a function of received power for the input 33% RZ-OOK and converted NRZ-OOK after different number of uniform FBG with 60% reflectivity cascades. Insets: eye diagrams of back to back 33% RZ-OOK signal and converted NRZ-OOK signals.

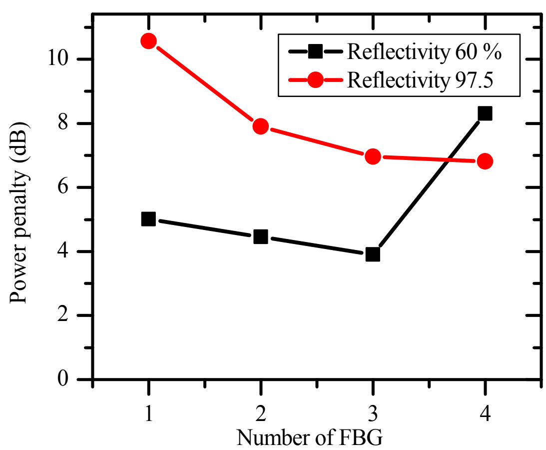

Figure 8. Power penalty (at BER= 10^{-9}) induced by cascading of a uniform FBG versus number of cascades for uniform FBG with different reflectivity shown in inset.

4. Conclusions

The cascadability of uniform fibre Bragg grating of 40 Gbit/s RZ-OOK to NRZ-OOK format conversion has been demonstrated numerically for the first time. The best BER performance is obtained after three cascades of uniform FBG with 60% reflectivity. It has been found that uniform FBG RZ-OOK to NRZ-OOK format converter must have Gaussian like pass band which is connected with rather low reflectivity value to reduce amplitude ripples in converted signal waveform and side lobe minimums must be chosen to match side tones of RZ-OOK signal for conversion.

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