Impairments on 40 Gbit/s per Channel WDM Optical System with Wavelength Conversion

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Abstract

High transport capacity optical networks, carrying information as fast as a few terabit by second, are now being developed. In this paper we discuss the major performance limiting factors imposed by each of the network's subsystems. Optical wavelength conversion in the network's nodes allows channel cross connecting without blocking probability. Thus, wavelength conversion based on four-wav-mixing inside semiconductor optical amplifiers is also discussed. Simulation results of a four-channel system with optical wavelength conversion and total capacity of 160 Gbit/s are presented.

I. INTRODUCTION

Nowadays the fast growing of services provided by telecommunications' operators, such as Internet, video conference and high definition television, requires a high transport capacity network. Single mode fibres with an available bandwidth around 50 THz are known to be a good solution. The wavelength multiplexing enables the transmission of hundreds of channels each one modulated at the bit rate allowed by the present high-speed electronics. Furthermore the data transport should get as closer as possible to the customers without electrical-optical conversion. In consequence we are leaving the long-haul point-to-point optical systems and evolving to more complicated network topologies. Thus, to understand the new optical systems and the impairments imposed by them on the network performance is of major importance.

II. OPTICAL NETWORK

The design of WDM optical networks with a bit rate per channel larger than 40 Gbit/s requires the knowledge of the impairments induced by each one of the network's subsystems. In this section we present each of the subsystems and their main design parameters as well the impairments they impose to the rest of the system.

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A. *WDM Transmitter*

The good quality of the transmitter output signal in a telecommunications network is a major requirement to achieve acceptable system's performance. Two characteristics define the quality of an optical source. First, the rate of spontaneous emission added to the laser mode, which leads to intensity noise. This characteristic is quantified by measuring the source signal to noise ratio (SNR). Second, the laser light spectrum broadening results in phase noise. This characteristic is quantified by measuring the laser linewidth. A WDM transmitter also requires the intensity modulation of the laser light. The Mach-Zehnder amplitude modulator (MZM) provides intensity modulation without inserting chirp. However the MZM extinction rate is a performance's limiting factor. The WDM transmitter can be achieved with an array of lasers emitting at different wavelengths. Other possible scheme is to divide the light of just one laser by an array of semiconductor optical amplifiers (SOA). Thus, pumping the SOA at different wavelengths we convert the laser light to different wavelengths. In the last case boost amplification of the converted channels is required. This amplification degrades the signal to noise ratio at the transmitter output. In this work we used an array of lasers emitting at the frequencies of 192.3, 192.5, 192.7 and 192.9 (THz). The four channels spaced of 200 GHz are multiplexed by means of an array waveguide grating (AWG). The figure 1 shows the optical spectrum of the WDM transmitter with a resolution of 0.1 nm. The light of the lasers' array, presenting a typical spectral linewidth of 10 MHz , is intensity modulated at rate of 40 Gbit/s.

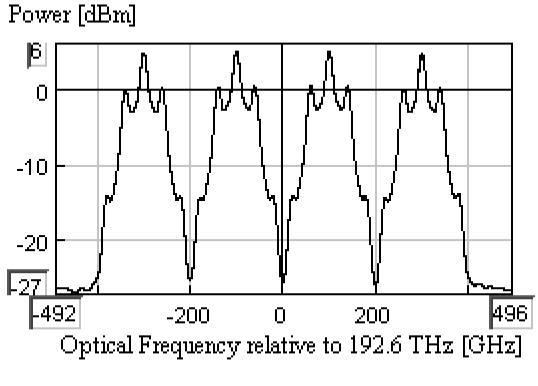

Fig. 1 Optical spectrum at the WDM transmitter output.

As we can see on the figure each channel presents a central peak, which corresponds to the light emitted by the laser, and two side peaks, 40 GHz far, which correspond to the modulation.

B. *Transmission*

The transmission medium used on the optical networks is the optical fibre. Transmission in such medium is affected by a large number of physical phenomena. Firstly the optical field attenuation resulting from Rayleigh scattering and silica absorption. Also attenuation peaks appear at 1385 nm due to the light absorption by the hydroxyl ions (OH-), a residual impurity from the fibre fabrication process. Special manufacturing processes produce fibres without this absorption peaks, allowing the transmission in a bandwidth of almost 50 THz [1]. Secondly the chromatic dispersion which corresponds to different wavelengths travelling at different speeds. The result is the pulse broadening leading to the intersymbol interference in the detection. Thirdly the polarization mode dispersion (PMD) which is due to the coupling of light to the two principal modes of the fibre, which typically are non-degenerated due to the fibre asymmetries. Moreover, at high optical power levels the light interacts with the fibre material producing a variety of non-linear effects. The dependence of the refractive index on the optical intensity leads to a variation on the pulse phase, which is known by self-phase modulation (SPM). When two different wavelengths cross the same medium we observe cross phase modulation. Also non-linear effects such as four-wave mixing (FWM), stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) affect the transmission.

The major limiting factor to the transmission over standard fibre at a bit rate of 40 Gbit/s per channel is the chromatic dispersion, not allowing total distances larger than 4 km [1]. However dispersion's compensating components are already well developed. A chirped fibre Bragg gratings (FBG) with a bandwidth of 10 nm to compensate the chromatic dispersion accumulated on the transmission over standard fibre was presented in 1999 by Morten [2]. Also fibre Bragg gratings, which allow compensation of both first and second order dispersion, have been developed [2]. Thus, nowadays the chromatic dispersion is easily overcome.

The standard fibre has a typical value of the PMD coefficient of 0.5 ($\mathrm{ps}/\sqrt{\mathrm{km}}$), which for long-haul systems becomes of major importance. When the average power launched into the fibre exceeds a few milliwatts the non-linear effects arise. The fast overlapping of the pulses resulting from the strong dispersion regime induces intra-channel non-linear effects [3]. The figure 2 shows the bit error rate (BER) dependence on the received average power for two schemes of dispersion compensation. The goal was to understand if the position of the chirped fibre Bragg grating on the fibre span was important. In the case of no presence of non-linear effects the position is arbitrary. However in the presence of non-linear effects we can observe in figure 2 that the ideal case is to positioning the FBG before the optical amplifier (post compensation scheme). The simulation was based on a channel at 40 Gbit/s transmitting over a total distance of 500 km with a fibber span of 100 km. As the figure shows at low levels of optical power the major limiting factor is the adding of amplified spontaneous emission noise (ASE) to the signal, in the amplifier stage, leading to a small value of the signal to noise ratio at the receiver input. As the signal power increases the SNR also increases and consequently the bit error decrease. However, as the power increase the intra-channel non-linear effects become dominant. The balance between the increasing of the SNR and the signal degradation due to the non-linear effects results in a point where the BER is minimum. As the graph shows this point is of 3 dBm and 8 dBm to the FBG positioned after and before the optical amplifier, respectively. We can also see that the system performance is better in the post compensation scheme than in the pre compensation. The explanation is that in the pre compensation the pulses overlap at higher power levels than in the post compensation case, enhancing this way the intra-channel non-linear effects. In agreement with this results we used in the system simulations a post compensation scheme launching at the fibre input an average power of 8 dBm.

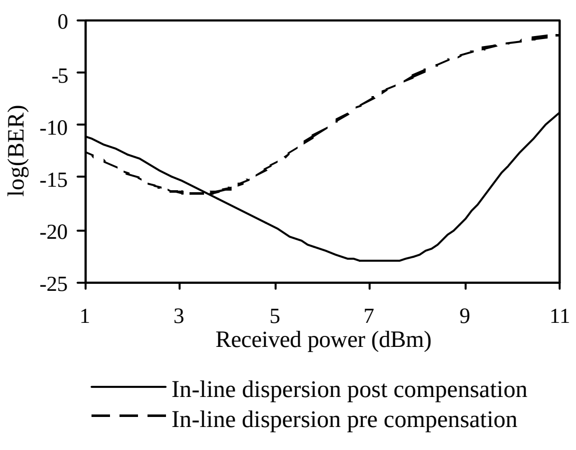

Fig. 2 Bit error rate versus received optical power, positioning the FBG after and before the in-line amplifier.

The non-linear effects between different channels, such as four-wave mixing and cross phase modulation also degrade the WDM transmission. However the pulses temporal evolution in a strong dispersion regime reduces the intensity of these effects becoming an impairment of small importance. When the number of channels is high, typically more than twenty-five, the average power inside of the fibre approaches the Raman effect's threshold, which results on a performance impairment due to the scattering of the signal light.

C. *Wavelength conversion*

Nowadays the optical networks are evolving from point-to-point to mesh topologies. The nodes of the network require cross-connects. Non-blocking cross-connects require wavelength conversion. Thus, all optical wavelength conversion (AOWC) is a fundamental process to achieve a transparent optical network. There is many different ways to get wavelength conversion such as cross gain modulation or cross phase modulation in semiconductor optical amplifiers and second order generation in passive waveguides. In this work we used wavelength conversion based on four wave mixing in semiconductor optical amplifiers. Conversion at 40 Gbit/s requires an AOWC model which takes in account the fast carrier pulsation due to the intraband processes such as carrier heating and spectral hole burning. Thus we have implemented in our simulation tool[1] the analytical model developed by Mecozzi to the four-wave mixing wavelength converter [4]. The figure 3 shows the wavelength conversion efficiency as the pump frequency detunes from the frequency of the input signal. We can observe the asymmetry between positive and negative detuning. In the positive detuning we convert the input signal frequency to a higher frequency while in the negative detuning we convert to a lower frequency.

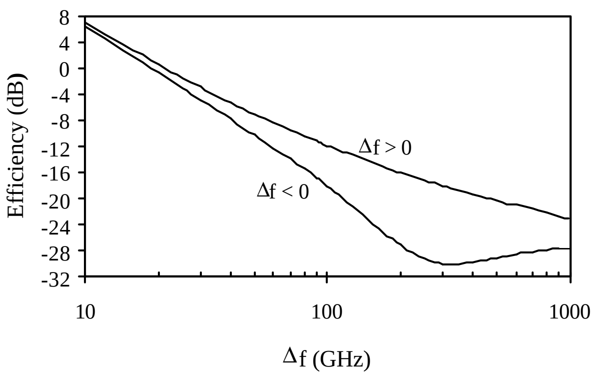

Fig. 3 The conversion efficiency as the pump frequency detunes from the signal frequency.

In the system simulation work the channel 192.5 THz is frequency converted to 193.1 THz at half of the system's total distance. The figure 3 shows that this conversion has an efficiency around –18 dB. The figure 4 shows the optical spectrum at the semiconductor optical amplifier (SOA) output. The scattering of the light by the grating formed from the beating between the signal and the pump produces new frequencies. In the figure 4 the frequency generated is called conjugate, because it has the same spectrum of the input signal but reversed. This propriety of the four wave mixing effect in SOA can also provide dispersion compensation.

The figure 4 also shows that wavelength conversion requires optical filtering. The most efficient way is to filter firstly the pump using a stop band (SB) optical filter centred on the pump frequency and secondly to filter the conjugate with a band pass optical filter (BP) centred on the frequency of the conjugate.

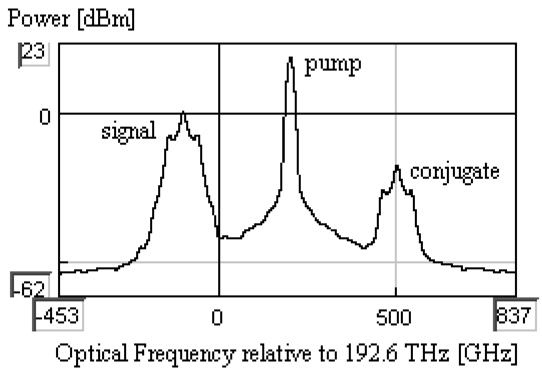

Fig. 4 Optical spectrum at the semiconductor optical amplifier output.

After filtering the converted signal, optical amplification is always required to equalizing the power level of the channel with the remaining non-converted channels. The figure 5 shows the schematic used on simulation to the optical wavelength converter. The demultiplexing is performed by a 1x4 array waveguide grating (AWG). Although the number of channels at the AOWC output is four, the multiplexing task requires a 5x1 AWG since the channels are not equally spaced. A polarization controller at the AOWC input is also necessary since the state of polarization is arbitrary and the frequency conversion by means of four-wave mixing in SOA is sensitive to the polarization.

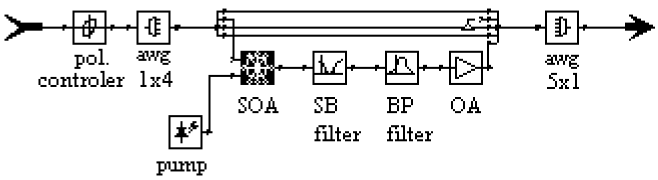

Fig. 5 Simulation set-up to the all-optical wavelength converter based on four-wave mixing in SOA.

Should be noticed that from wavelength conversion results an impairment to the system performance. As the conversion efficiency is small, boost amplification of the channel is required decreasing this way its signal to noise ratio. However, our simulation results showed this not to be a major impairment.

The figure 6 shows the WDM optical spectrum after wavelength conversion. Should be noticed that the 40 GHz modulation peaks decreased which results in a degradation of the signal temporal shape. This is a consequence of cascade optical filtering.

[1] Photonic Transmission Design Suite by Virtual Photonics Incorporated.

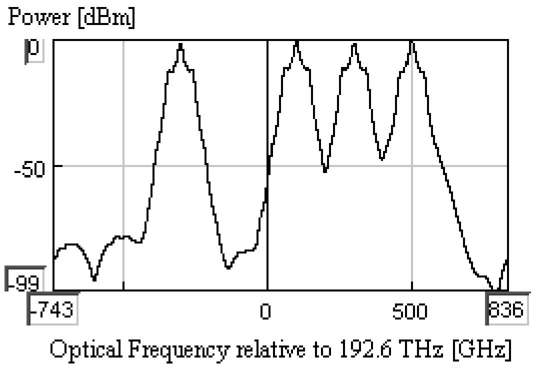

Fig. 6 Optical spectrum after wavelength conversion.

B. *WDM Receptor*

The last subsystem of an optical network is the receptor. Current optical systems are based on intensity modulation and direct detection by means of a PIN or APD photodetector. Thus a WDM receptor basically consists of a demultiplexing filter (ex.: AWG 1xN), a photodetector, an electrical filter and a decision circuit. The major factors limiting the system performance at reception is the thermal and shot noise associated with the direct detection.

III. SYSTEM SIMULATION

In this section we describe the simulation results to the performance of a four-channel WDM optical system with a total distance of 500 km. In the design subsection we present the system simulation's set-up considering the compensation of the major performance limiting factors. In the performance subsection we present the simulation results by means of eye diagrams and the quality factor (Q).

A. *Design*

In section II we presented the chromatic dispersion, intra-channel non-linear effects and the adding of ASE noise to the signal as the major system's performance limiting factors. The adding of the ASE noise cannot be avoided. However we can assure the signal to noise ratio at the receptor input if we impose a value to the transmitter signal to noise ratio. The chromatic dispersion is compensated by means of a fibre Bragg grating which simple model consists of a transfer function opposite to the fibre. No second order dispersion compensation is providing. The intra-channel non-linear effects are partially compensated by means of a dispersion map based on the work done by [3]. As the figure 7 shows the transmission link begins with 820 meters of dispersion compensation fibre (DCF) providing the pre-chirp necessary to intra-channel non linear effects compensation. Transmission over a span of 300 kilometres, over standard fibre, is performed before wavelength converting the channel 192.5 to 193.1 THz. The conversion is based on the model discussed on the section II.C. The optical amplifiers are based on the flat gain model with small signal gain of 25 dB, a saturation power of 15 milliwatts and a noise figure of 6 dB. The variable optical attenuator (VOA) represents the signal losses at the rack interconnections. A standard fibre with a length of 5300 meters performs the post-chirp required to achieve a zero average level of dispersion. The receptor consists of a photodetector PIN with a spectral thermal noise density of 10^{-10} A/$\sqrt{\mathrm{Hz}}$ and a gaussian electrical filter with a bandwidth of 30 GHz.

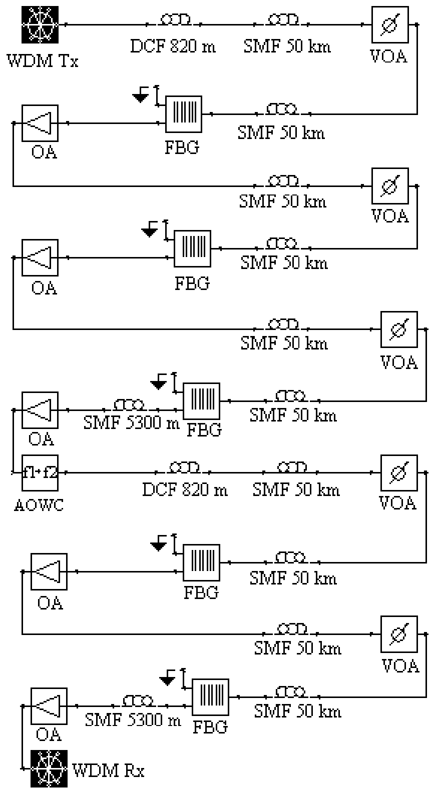

Fig. 7 System simulation's set-up.

B. *Performance*

In this subsection we present the results to the simulation of the system presented in subsection A. The performance is evaluated inserting gradually the different limiting factors. The eye diagram and the quality factor were computed in each step, and here we present the channel with worst performance.

The figure 8 shows the eye diagram when the only limiting factors are the PIN noise and the transmitter SNR. The non-linear effects, the chromatic dispersion as well the adding of the ASE noise were not considered. The quality factor associated with the eye diagram has a value of 23.

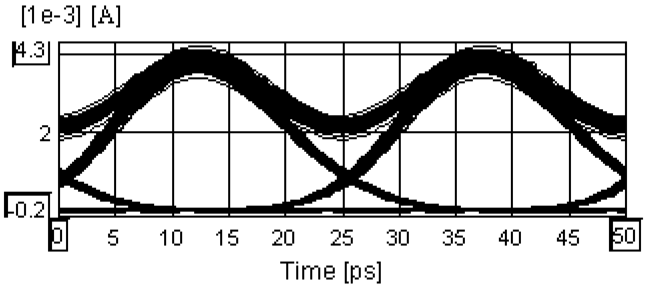

Fig. 8 PIN noise plus source SNR.

The figure 9 shows the eye diagram when the limiting factors are the PIN noise, the transmitter SNR and the adding of ASE noise to the signal. The non-linear effects and the chromatic dispersion were not considered. The quality factor associated with the eye diagram has a value of 8.4.

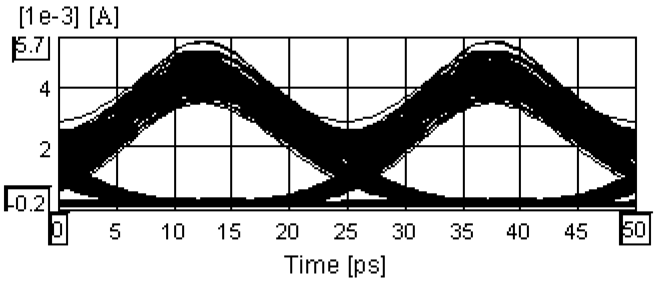

Fig. 9 Adding ASE noise.

The figure 10 shows the eye diagram when the limiting factors are the PIN noise, the transmitter SNR, the adding of ASE noise to the signal. The non-linear effects are partially compensated and the chromatic dispersion is full compensated. The quality factor associated with the eye diagram has a value of 7.1.

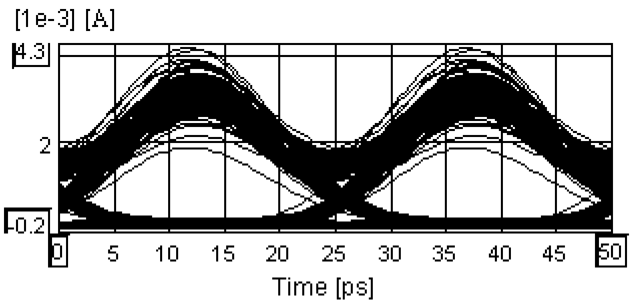

Fig. 10 Non-linear effects partially compensated while chromatic dispersion is full compensated.

The figure 11 shows the eye diagram when the limiting factors are the PIN noise, the transmitter SNR, the adding of ASE noise to the signal and the second order dispersion. The non-linear effects are partially compensated and the chromatic dispersion is full compensated. The quality factor associated with the eye diagram has a value of 5.5.

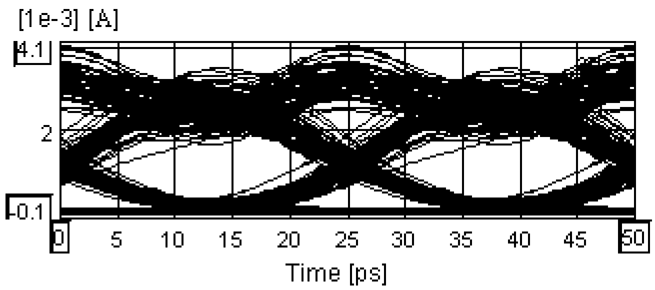

Fig. 11 Second order dispersion.

IV. CONCLUSION

In this paper we presented a four-channel WDM optical system with a bit rate per channel of 40 Gbit/s over a total distance of 500 km. Also in–line wavelength conversion of one channel is performed. The simulation results showed that major limiting factors are the chromatic dispersion and the intra-channel non-linear effects. A dispersion map can provide full chromatic dispersion compensation as well partial non-linear effects compensation. Thus the remaining factors are the adding of the ASE noise to the signal, the source signal to noise ratio, second order dispersion and polarization mode dispersion. We observed that the channel wavelength conversion was not a major impairment. The design of the system as showed in the section III led to a system performance with a bit error rate smaller than 10^{-12}, when second order dispersion and the PMD effect are not considered. However the signal to noise ratio of the source must be larger than 27 dB. The simulation results also showed that in agreement with a BER smaller than 10^{-12}, second order dispersion and PMD compensation must be compensated.

V. REFERENCES

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