Use of SOA in managing the effects of chromatic dispersion in optical systems – A Review

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Abstract— With increasing demands of bandwidth in communication systems, the data rates are increasing due to which chromatic dispersion(CD) effects in optical communication systems also increase. As the data rates are increased, the inter-bit distances decrease, therefore, the bits will tend to broaden due to CD, and will cause inter-symbolic interference(ISI). Various techniques have been used in the literature to manage these effects such as dispersion compensating fibres(DCF), fibre bragg gratings(FBGs), Arrayed waveguide gratings(AWGs), etc. But these techniques possess many limitations like insertion losses, small compensation range, etc. Also, a tunable system cannot be constructed, because we have to know about the fibre length beforehand to apply these techniques. Therefore, the use of Semiconductor optical amplifier(SOA) was exploited in providing a tunable compensation of CD in various optical systems. This paper provides a review of the various optical systems in which SOA has been used to mitigate CD.

Keywords— Chromatic dispersion; Gain saturation; Optical communication systems; Semiconductor optical amplifier **.**

I. INTRODUCTION

In high speed optical fibre communication systems, the effects of chromatic dispersion limits the distance and bit rate of the system. In optical systems, dispersion is defined as a pulse spreading with respect to time. When a light pulse passes through an optical fibre, the core diameter, refractive index, wavelength, etc. causes pulse broadening [1]. This will have a severe effect on optical communication systems. As the bit rate of the system will increase, the inter-bit distance will decrease, and hence with the effect of chromatic dispersion, these bits will broaden in time, and hence overlap each other while travelling inside the fibre, and we will get distorted output. This overlapping of bits in known as Inter-symbolic Interference (ISI). Due to this, the BER of the system increase, and hence the system performance decreases. In the standard SMF-28 fibre, the width of the signal pulse increases by a rate of 16 ps/km. Therefore, there is a need to develop techniques to reduce the effects of chromatic dispersion to get increased system performance in terms of transmission distance and bit rate.

Generally, DCF (Dispersion compensating fibres) are used in the optical fibre communication systems with known fibre lengths [2]. But, at very-high data rates, if a new user wants to access the network with an optical fibre link of unknown length, a technique with automatic dispersion compensation will provide error free communication and more flexibility in operating optical networks [3]. Hence, an automated technique need to be developed for management of chromatic dispersion effects. Various techniques have been developed in the past to mitigate the chromatic dispersion effects in optical fibre communication systems.

In [4], Planar Lightwave Circuit (PLC) was used as an optical dispersion equalizer in a 2.5 Gb/s transmission system. The maximum dispersion value obtained was 836 ps/nm in the 1.55 μm region, but there was an insertion loss of 3.5 dB. In [5], the properties of a structure consisting of two cascaded arrayed waveguide gratings (AWGs) , including a lens in its middle focus plane, were investigated for dispersion compensation. It was shown that by changing the coefficient of the lens's parabolic phase signature, the chromatic dispersion of the component can be changed. In [6], an optical tunable chromatic dispersion compensator was presented that was based on a virtually imaged phased array (VIPA) and spatial light modulator (SLM) that provided both positive and negative dispersion. The tunable chromatic dispersion compensator provided chromatic dispersion compensation of -4080 ~ +850 ps/nm. In [7], tunable dispersion compensation using non-linearly chirped fibre bragg gratings (FBGs) was demonstrated. In most of these techniques, there are limitations such as the insertion losses and/or the dispersion-compensation range is reduced by an intra-channel third order dispersion.

Therefore, the use of Semiconductor Optical Amplifier (SOA) was exploited. SOA is advantageous over other techniques because it provides an easy tunable approach to CD compensation. SOA is used based on a concept that exploits changes in the refractive index and gain of the SOA. These changes can be introduced broadly in two ways :

i. By changing the SOA bias current.
ii. By SOA gain depletion.

These changes will cause variations in SOA's refractive index [8]. The interaction between the chirp introduced by these SOA changes and incoming data pulses affected by CD can be exploited for managing CD effects.

This phenomenon of SOA will be further discussed in section 2. Section 3 describes the use of SOA in managing chromatic dispersion in various optical systems .

II. THEORETICAL BACKGROUND OF SEMICONDUCTOR OPTICAL AMPLIFIER (SOA)

The chirp parameter of SOA is

$$\alpha = \frac{2Id\varphi}{dI} \qquad (1)$$

where I and φ are optical intensity and phase of output electric field respectively. In SOA, both intensity change ΔI and phase change $\Delta\varphi$ are caused by carrier density change ΔN . The carrier density equation is determined by the rate equation

$$\frac{dN}{dt} = -\frac{N}{\tau} - A_g(N - N_o)\frac{I}{h\mu} + \frac{J}{ed} \qquad (2)$$

and optical intensity I is determined by

$$\frac{dI}{dz} = \Gamma A_g(N - N_o) \qquad (3)$$

where τ, $A_g, N_o, h\mu, J, e, d, and\ \Gamma$ are carrier lifetime, differential gain, transparent carrier density, photon energy, injection current density, electron charge, active layer thickness, and optical confinement factor, respectively.

Assuming that ΔN is uniform in SOA, gain change ΔG(in dB units) and $\Delta\varphi$ is expressed as :

$$\Delta G = 10\log_{10} e\,.\,\Gamma A_g \Delta NL, \qquad (4)$$

and

$$\Delta\varphi = -\frac{2\pi}{\lambda}\Delta nL = \frac{\alpha'}{2}\Gamma A_g \Delta NL \qquad (5)$$

where λ,n and L are wavelength, refractive index and device length respectively. And α' is the linewidth enhancement factor of semiconductor material, which is defined as :

$$\alpha' = -\frac{4\pi}{\lambda}\frac{\left(\frac{\partial n}{\partial N}\right)}{\Gamma A_g} \qquad (6)$$

From (1),(4) and (5), we can obtain the chirp parameter of the SOA as,

$$\alpha = \alpha' \frac{dG}{dP_{out}} = \alpha' \frac{\left(\frac{dG}{dP_{in}}\right)}{1+\left(\frac{dG}{dP_{in}}\right)} \qquad (7)$$

where P_{in} and P_{out} are the SOA input and output power respectively. When the optical input power is low enough, (7) gives $\alpha = o$, because the carrier density remains unchanged to the value at the equilibrium ($\Delta N = 0$) and $\frac{dG}{dP_{in}} = 0$. However, as the optical power increases, carrier depletion occurs in SOA ($\Delta N < 0$) and this induces gain saturation ($\frac{dG}{dP_{in}} < 0$) . Since $\alpha' > 0$ in gain medium such as SOA, the chirp parameter is negative ($\alpha < 0$) for the SOA under gain saturated condition.

Hence, the SOA can be used in managing dispersion as due to dispersion, positive chirp is introduced in the system, therefore, by using SOA in gain saturation region, this positive chirp is compensated with the negative chirp of SOA.

Also, by varying the SOA drive current i.e. by varying the SOA gain, the carrier density inside of the SOA varies; as a result the refractive index of SOA also changes which subsequently broadens or compresses the passing signal pulse-width [3]. This is a result of changes of a real and imaginary part of a dielectric constant of the SOA (it's waveguide medium), which are related by Kramers-Kronig(KK) dispersion relations. The complex refractive index of SOA can be represented by :

$$n = n_o + \Delta n' + i\Delta n'' \qquad (8)$$

Here, $\Delta n' + i\Delta n''$ represent the real and imaginary part of refractive index changes due to the carrier density changes by current injection; n_o is the real part of the SOA refractive index. Considering n_o as a constant, through Kramers-Kronig(KK) relation, we can mathematically show :

$$\Delta n'(E) = \frac{2}{\pi}P\int_0^\infty \frac{E'\Delta n''(E')dE'}{E'^2 - E^2} =$$

$$= -\frac{1}{2\pi^2}P\int_0^\infty \frac{\Delta g(E')dE'}{E'^2 - E^2} \qquad (9)$$

Here, P denotes the principal value integral and Δg is the gain change. From the above equation, we can find the relationship between SOA gain changes which then affects the refractive index changes of the SOA and thereby result in compression or expansion of optical pulse which passes through the SOA. This concept can also be used to manage the dispersion effects in optical communication systems.

III. Use Of SOA In Managing Dispersion

We have seen that SOA can be used to manage the effects of dispersion by operating it in gain saturation region. In this region SOA produces negative chirp which compensates for the positive chirp created by dispersion. Another method of using SOA to manage dispersion effects is to introduce gain changes by changing the current. It causes refractive index changes, which can be used to broaden or compress the incoming pulses. SOA has been used in various optical systems and chromatic dispersion was managed successfully by exploiting both the concepts of negative chirp and gain changes in the SOA. This section provides a review of all the optical communication systems in which SOA's have been used to manage the chromatic dispersion.

A. *Transmission performance of a chirp controlled signal using SOA*

The fibre transmission performance of the optical signal whose chirp was controlled by utilizing phase modulation in SOA was examined.[9] This chirp control technique converts a positive chirp created by electro-absorption(EA) modulator into negative chirp, which reduces the waveform degradation due to the chromatic dispersion in transmission over standard single mode fibre (SMF). The SOA input power and the carrier lifetime affected the chirp control. As the input power increases, the negative chirp became large, while the waveform was largely distorted due to gain saturation. However, the wave distortion at high SOA input powers can be shaped by using a frequency discriminator. The acceleration of the carrier lifetime also reduces the waveform distortion due to gain saturation. SOA also provides an optical gain that is sufficient to compensate the insertion loss of the EA modulator. It was demonstrated that the chirp control technique is effective even for a high bit rate optical signal up to 10 Gb/s, when the carrier lifetime of SOA is expedited by optical pumping.

B. Reduction of dispersion-induced effects in microwave optical links.

Conventional microwave optical transmissions operating near 1550 nm are severely limited by the chromatic dispersion of standard single mode fibres. This limitation mainly consists of the radio-frequency (RF) carrier suppression effect due to dispersion-induced sideband cancellations at certain combinations of microwave frequencies and propagation distances. An approach to reduce the dispersion-induced effects in microwave-optical links based on the interplay of intensity dependent phase modulation in SOA's and fibre chromatic dispersion was demonstrated [10]. It was shown that the dispersion-induced radio-frequency carrier suppression ratio can be alleviated by more than 20dB when the SOA is operated under saturation.

C. Reduction of dispersion-effects in analog optical transmission.

A technique to improve an analog optical transmission performance by reducing the non-linearity and chromatic dispersion induced carrier suppression was proposed [11]. Chromatic dispersion in an optical link causes the dispersion induced carrier suppression(DICS) and dispersion induced distortion(DID) effect. Here, the enhancement of transmission performance in Mach–Zehnder modulator (MZM) modulated analog optical link by using semiconductor optical amplifier (SOA) was proposed. SOA was used to provide the negative chirp characteristic and suppress the intrinsic non-linear distortion component of modulator at the same time. An SOA is known to have the negative chip characteristics. The negative chirp occurs when SOA operates in gain saturation region. Therefore, SOA could be used to compensate the positive chirp characteristic of modulator. Also, the simultaneous improvement in DICS and DID performance of an analog link was also achieved by using SOA in conjunction with MZM.

D. Tunable CD management using chirp control in SOA.

A tunable CD compensation technique was demonstrated using SOA and a coil of Dispersion Compensation fibre(DCF)[12]. This technique is based on chirp control using a SOA. By injecting a clock pulse into a SOA together with the received signal, the chirp of the received signal can be fine-tuned based on cross-phase modulation (XPM) in the SOA. The tuning method is fast and accurate, which is realized by controlling the drive current of the SOA, and the power of clock pulse. The injected clock pulse can modulate the carrier density of the SOA, and then the chirp of the signal can be adjusted based on XPM. In this way, a 10 Gbit/s tunable compensation setup , ranging from -40ps/nm to 60ps/nm , was realized without changing the length of the DCF. The tuning range was limited only by the maximum input power and the maximum drive current the SOA can handle. Other advantages, such as polarization independence and high operation speed could be obtained using a higher performance SOA.

E. Dispersion managed fibre-ring resonator using SOA.

A hybrid model was proposed in order to use the design of compensating SOAs non-linearity by adjusting cavity dispersion in a SOA fibre ring mode-locked laser [13]. It was shown that once the cavity dispersion is correctly adjusted, the mode-locked pulses of 10 ps width become distortion free gaussians, with their Time-Bandwidth (TB) product very close to the fundamental gaussian limit (TB=1/2).

F. Management of dispersion-affected auto-correlation in an OCDMA system.

Distortion of the optical code division multiple access (OCDMA) auto-correlation width by fibre chromatic dispersion can severely influence incoherent OCDMA transmission based on picosecond multiwavelength pulses. For the first time, the use of a semiconductor optical amplifier (SOA) for manipulation of the OCDMA auto-correlation consisting of multiwavelength code carriers in order to provide needed compensation was used [14]. The OCDMA transmission system was based on two-dimensional wavelength-hopping time spreading codes with 8 ps multiwavelength pulses as the code carriers. Different techniques deploying an SOA for auto-correlation width adjustments were investigated and their effectiveness was subsequently verified on the OCDMA transmission through a 17 km long fiber-optic testbed connecting Strathclyde and Glasgow Universities.

G. Managing chirp of OCDMA code carriers in temperature affected fibre link.

Chromatic and temperature induced dispersion severely affects OCDMA systems with multi-wavelength ps code carriers. Even a small change in dispersion can severely effect the system performance, cardinality, transmission distance ,etc. Therefore the use of SOA was employed here to manage dispersion [15]. The investigation was done using a 19.5 km long fibre transmission link that was exposed to different temperatures (20°C and 50°C) using an environmental chamber. By placing the SOA on a transmission site and using it to manipulate the code carrier's chirp via SOA bias adjustments, it was shown that this approach could successfully control the overall fibre link dispersion, and it could also mitigate the impact on the received OCDMA auto-correlation and its FWHM.

IV. Conclusion

Semiconductor optical amplifier exhibits characteristics that produce negative chirp when operated in gain saturated region. This property can be used to manage dispersion effects by converting the positive chirp created by dispersion into negative chirp. We have presented a review of all the systems in which SOA has been employed to manage dispersion effects.

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