REDUCTION OF DISPERSION INDUCED DISTORTIONS BY SEMICONDUCTOR OPTICAL AMPLIFIERS

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Abstract   An approach is presented to reduce the chromatic dispersion-induced distortions in optical links carrying combined baseband and microwave signals. This new method is based on the interplay of intensity dependent phase modulation in semiconductor optical amplifiers (SOAs) and fiber nonlinearities. Theoretical and experimental results are demonstrated for a 400 km long optical link.

Introduction
Conventional microwave optical transmissions are severely deteriorated by the chromatic dispersion of optical link using standard single mode optical fiber near 1550nm. This limitation mainly is caused by the radio-frequency (RF) carrier suppression effect due to dispersion-induced sideband cancellations at certain combinations of microwave frequencies and propagation distances [1]. Several techniques have been proposed to overcome this effect such as optical single sideband (SSB) modulation [2], chirped fiber gratings [3], variable chirp in electroabsorption modulators [4], self-phase modulation effect introduced by the fiber [5], dual mode lasers [6], midway optical phase conjugation, etc.

In this letter, two approaches to overcome dispersion-induced effects based on fiber nonlinearities and adjusting the chirp and phase modulation generated by saturated semiconductor optical amplifiers (SOAs) are investigated. The results show that the fading of the RF-to-RF system response can be significantly alleviated.

System concept
The studied system is a 400km optical fiber link, located in Sweden, between Kista and Hudiksvall. Uplink transportation of digital signal upconverted to 40GHz subcarrier and combined with a 2.5Gbps digital baseband data stream over the optical fiber has been investigated. Standard single mode fiber is applied, the total fiber attenuation is lower than 80dB and it is compensated by EDFAs. So the power is kept between -8dBm and +8dBm at all points of the link.

The baseband modulation generates two sidebands and the double sideband modulated subcarrier will generate additional spectral components. If the subcarrier itself is strong enough compared to modulation, each subcarrier sideband can be regarded as an intensity modulated optical carrier.

At the receiver Fiber Bragg Grating is applied. It reflects and filters out one of the two modulated optical subcarrier sidebands, which via the circulator was direct detected by a PIN diode. Fig.1. shows the simplified system block diagram. The transmission is limited by the optical signal to noise ratio and the chromatic dispersion. The dispersion affects the baseband datastream and datastream on subcarrier with the same level.

Fig.1. Simplified system setup

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Chromatic Dispersion Penalty

The intensity modulation generates optical double sidebands. A phase difference is realized between the two sidebands due to the chromatic dispersion. So periodic reduction of the received RF carrier power is observed in Fig.2. The dispersion limit for about 1 dB optical power penalty is estimated by [7]

$$B = \frac{c}{\sqrt{2 \cdot \lambda^2 \cdot D \cdot L}}$$

In our system this limit is 3.2Gbps. If the datastreams are lower, the data transmission is limited by the optical signal-to-noise ratio. In case of higher data speed dispersion compensation techniques will be necessary. Using directly modulated laser diodes or unbalanced external modulator the maximum link length is expected to be much smaller due to the positive chirping of the optical transmitter.

![Fig.2. Dispersion Penalty over 400km fiber](image)

Fig.2. Dispersion Penalty over 400km fiber

Fig.3. represents the baseband Eye diagram degradation assuming a chirp-free transmitter. The BER in a dispersion limited system deteriorates versus the fiber length and data speed. In a practical system the fiber length isn’t a free parameter, hence the required BER determines the applicable modulation bandwidth (Fig.4).

![Fig.3. Eye diagrams at input and output (400km)](image)

![Fig.4. Simulated BER versus data speed for different link length](image)

Fiber nonlinearities

With the increase of input optical power provided by high intensity laser diodes, non-linearity of optical fiber can no longer be neglected. A given density of photon flux self-phase modulation (SPM) can become significant and one must consider the distortions caused by SPM during the design process of microwave optical systems.

![Fig.5. Measurement results over 30 km fiber at four different average input intensities](image)

![Fig.6. Simulation results over 400km fiber at different average input intensities](image)
At high input intensity modifies the transfer function of the fiber and can compensate modulation suppression caused by dispersion. As the signal intensity increases the notches caused by dispersion shift to higher modulation frequencies (Fig.5. and Fig.6). The measurement and simulation results show the fiber-induced SPM less influence of equalization of the frequency notches in the studied system (optical power < 8dBm).

**SOA based Dispersion Compensation**

When the incoming optical power of the laser amplifier is intensity modulated, the optical gain is affected in both magnitude and phase via the modulation of the complex refractive index caused by the electron density. Consequently, in SOA the optical signal becomes amplitude modulated (AM) and phase modulated (PM) caused by carrier density change. It is fundamental to know the behavior of the refractive index within the active region. It can be modeled using the Linewidth Enhancement Factor (LEF=Henry factor= α factor) approximation. Measurements of LEF can be found in the literature and have shown that LEF is not a mere constant factor, but it is for instance a function of bias current, wavelength and input optical power. In the unsaturated region the LEF value ranges from 2 to 7 for GaAs and GaInAsP conventional lasers and from 1.5 to 2 for quantum well lasers. However, as the optical input power (\(P_{in}\)) increases, carrier depletion occurs in SOA and this induces gain saturation. In optical amplifiers under saturation conditions, an increasing input intensity causes a decrease in the amplifier gain (\(dG/dP_{in}<0\)). In this case LEF can be calculated from the unsaturated LEF value (LEF_{unsat}):

\[
LEF = LEF_{unsat} \frac{dG}{dP_{out}} = LEF_{unsat} \frac{dG/dP_{in}}{1 + (dP_{out}/dP_{in})}
\]

The chirping parameter which is positive for light sources and unsaturated optical amplifiers is negative for saturated amplifiers. Fig.7 represents the optical gain and the LEF dependence on the optical power. When the input power becomes larger than the saturation value, the chirp parameter rapidly falls to a negative value.

The chirp of saturated SOA cancels the positive chirp-parameter of modulator, enhancement the transmission distance and operating frequency, finally the optical amplification causes RF signal gain. However the SOA adds significant noise to the system. The negative chirp affects double sidebands and then causes the asymmetrical optical power between sidebands. As a result, the RF carrier suppression effect was reduced. The frequency transfer function between the intensity modulations at the input and output can be written:

\[
H_{int}(f) = \cos \left( \frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c} \right) - LEF \cdot \sin \left( \frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c} \right) + j \cdot LEF \cdot \frac{f}{f_c} \cdot \sin \left( \frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c} \right)
\]

D is the fiber dispersion, L is the fiber length, f is the modulation frequency, c is the light speed is vacuum, \(\lambda\) is the operating wavelength, \(f_c\) is the crossover frequency between adiabatic and transient chirp regimes.

Simulation was performed before the field trial. The simulated RF responses of 400 km fiber for different chirp parameters of the optical transmitter are depicted in Fig.8. All the results have been calculated for an optical input power of 0 dBm in order to reduce the influence of the nonlinear effects at the fiber. By comparing the results to the reference case of a zero-chirp situation (LEF=0), for LEF>0, the bandwidth of the system is reduced, while for LEF<0, the achievable bandwidth increases.

Preliminary experimental work was executed in our lab over 30 and 50 km fiber. The SOA under test was driven by different bias (dc) currents. The polarization state of the incoming optical power was optimized by polarization controller. The harmful effect of the optical reflection was eliminated by optical isolators. The required optical power and wavelength were produced by a tunable laser source. The intensity modulated optical signal was detected by a photodetector. The setup was controlled by a computer program, hence the measurement parameters were carefully set by the program and the measurement results were processed and stored. The RF response was measured with different parameters (Fig.9). As the SOA bias current (optical gain) increases the frequency notches of the RF response are reduced and shifted to higher modulation frequencies. The SOA device modifies the harmonic generation, too. The depths of harmonic rejections are not reduced significantly, but there frequencies are shifted a bit.
Based on the results, we may conclude that the interplay of adiabatic chirp generated by the saturated SOA and chromatic dispersion enables a significant reduction of the dispersion-induced effect. Introducing the frequency and optical power dependence in the SOA chirp model is required in the future.

Fig. 8. Theoretical responses of the optical link for different SOA chirp parameters.

Fig. 9. Measured RF response with SOA, normalized to back-to-back optical link

Conclusion
An approach to overcome the RF carrier suppression effect in microwave optical links based on the joint effect of SOA chirp, chromatic dispersion and nonlinearities in optical fiber has been proposed. The experimental results show that the frequency notches caused by the dispersion-induced carrier suppression effect may be sharply alleviated and the transmitted digital signal performance (eye diagram, BER, etc.) can be improved.

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