A multi-wavelength optical source for synchronous and asynchronous data transfer at a minimum of $16 \times 10$ Gbps

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Abstract

Numerical calculations have been carried out to study the characteristics of a multi-channel optical source capable of delivering (i) picosecond pulses with 10 GHz repetition rate at 16 different wavelengths and (ii) at least 16 channel multi-wavelength single mode CW output with precise 40 GHz channel spacing for application to fiber communication. In the first scheme, the pulse characteristics like power variation, pulse width and de-synchronization across the 16 demultiplexed channels are numerically investigated. The pulse width is observed to be almost constant ($\sim 13$ ps) in all the channels. The suitability of dispersion flattened fiber and dispersion shifted fiber as supercontinuum fiber is analyzed from the viewpoint of power variation and de-synchronization. In the second scheme a negligible power variation is observed across the 16 CW channels. The advantage of the proposed scheme lies in obtaining easy up-gradation with ultra-stable pulse train. The first scheme is suitable only for synchronous data transfer while the second scheme can be used also for asynchronous data transfer.

Keywords: Wavelength division multiplexing; Spread spectrum communication; Demultiplexing

1. Introduction

Dense wavelength division multiplexing (DWDM) and bit-parallel wavelength division multiplexing (BP-WDM) are key technologies in high-speed optical communication net-
works. When many WDM channels are required and/or in synchronous applications such as BP-WDM, it becomes very expensive to provide wavelength-stabilized source for each channel. The most cost-effective alternative is to spectrally slice the output of a single broadband source to get multi-wavelength GHz output [1] or multi-wavelength CW optical output [2] for subsequent modulation. The generation of high bit-rate spectrally enriched pulse train is an effective way for realizing a multi-wavelength source [3]. It is common knowledge that beat signal at GHz rep-rate can be generated by combining the output of two narrow line-width CW laser diodes operated at slightly different wavelengths [4,5]. In our earlier work, we had investigated the amplified beat signal shaped by passing through a suitable combination of single mode fiber and nonlinear optical loop mirror (NOLM) to get a pedestal free pulse train [3]. Some other techniques to generate high-rep-rate spectrally enriched pulses use harmonic mode-locking, passive mode-locking etc. The scheme proposed here has the flexibility for easy up-gradation to higher bit-rates of tens of GHz without the use of cumbersome RF electronic circuitry. The problems of pulse break-up and environmental instabilities that are common with the other approaches are not envisaged here. In addition, since the adjacent soliton-like shaped pulses have a phase difference of \(\pi\) radians, they will maintain an inherent ultra-stable period-to-duration ratio, which is difficult to attain in other schemes due to temporal instabilities. These high rep-rate pulses can be further spectrally enriched through supercontinuum (SC) process [6–10]. Lastly they can be sliced by a (i) WDM demultiplexer (DEMUX) of bandwidth at least 4–5 times larger than the beat frequency to get multi-wavelength GHz output or (ii) narrow bandwidth arrayed waveguide grating (AWG) DEMUX to get multi-wavelength single mode CW optical output.

In this work, we propose an all-optic, fiber based, scalable WDM source capable of delivering (a) optical pulse trains at 10 GHz repetition rate at a minimum of 16 different optical wavelengths separated by 100 GHz in ITU-T DWDM grid and (b) at least 16 channels multi-wavelength CW output with 40 GHz channel spacing, in which individual channels can be safely modulated at 10 Gbps.

2. Theory

The evolution of an optical pulse propagating through an optical fiber obeys the nonlinear Schröedinger equation (NLSE) given by [11]

\[
\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A - i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + i \gamma \left[ |A|^2 A - T_R A \frac{\partial |A|^2}{\partial T} \right].
\] (1)

In the above equation, \(A\) denotes the complex amplitude of the slowly varying optical field and \(T\) is the time measured in the frame of reference which is moving with the pulse. The first term on the right hand side of the above equation is the loss term, the second term governs the effect of second order dispersion, the third term accounts for the third order dispersion effects, and the fourth term takes in to account the effect of self-phase modulation (SPM), where \(\gamma = 2\pi n_2 / \lambda A_{\text{eff}}\) is the nonlinear parameter \((n_2\) is the intensity dependent refractive index and \(A_{\text{eff}}\) is the effective core area of the fiber). The last term in the above equation has its origin in the delayed Raman response and gives rise to
Raman self-frequency shift due to the intrapulse Raman scattering. The third order dispersion ($\beta_3$) becomes important for pulses of short duration where group velocity dispersion cannot be treated as constant and its wavelength dependence should be included. This term is significant when the optical wavelength nearly coincides with the zero dispersion wavelength. $T_R$ can be related to the slope of the Raman gain spectrum and its value is taken to be 3 fs, wherever included in this work. This term becomes important and should be included for short pulses with a broad spectrum. In such a case lower frequency components of the pulse get amplified at the expense of the higher frequency components of the same pulse due to the energy transfer from higher frequency components to the lower frequency components [11]. This phenomenon is called intrapulse Raman scattering. Due to this reason, the pulse spectrum shifts towards the low frequency side as the pulse propagates down the fiber. It is important to note here that we have considered an approximate form of the Raman term, which assumes Raman gain spectrum to vary linearly with the frequency across the pulse spectrum [11]. Such an approximation becomes questionable for ultra-short pulses, as Raman gain does not vary linearly across their entire spectrum. However, we may still choose to work with an approximate form, as input pulse widths in any of the cases discussed below is not less than 1 ps. The nonlinear parameter ($\gamma$) for all the fibers, in the following discussion, is taken to be 2.6 W$^{-1}$ km$^{-1}$ and the loss is taken to be 0.2 dB km$^{-1}$.

In this work, an optical beat signal is considered as the input. NOLM can be used to shape this beat signal. An NOLM is an all-fiber version of a Sagnac interferometer. It consists of a long length of fiber spliced to the output ports of $2 \times 2$ coupler. The input field entering the NOLM ($A_0$) is split into two parts, viz. forward and backward fields given by

$$A_f = \sqrt{f} A_0, \quad A_b = i \sqrt{(1-f)} A_0,$$

where $f$: $(1-f)$ is the splitting ratio of the coupler. Propagation of the above counter-propagating fields is governed by Eq. (1). After propagating the loop of length $L$, these two fields reaching the coupler take the following form:

$$A'_f(L, T) = A_f(L, T) \exp(i\phi_f), \quad A'_b(L, T) = A_b(L, T) \exp(i\phi_b),$$

where $\phi_f$ and $\phi_b$ are the phase (combined dispersive and nonlinear) acquired by the forward and backward propagating fields, respectively. The transmitted and reflected fields $A_t$ and $A_r$ at the output port of the coupler can be evaluated by

$$\begin{bmatrix} A_t \\ A_r \end{bmatrix} = \begin{bmatrix} \sqrt{T} & i \sqrt{(1-T)} \\ i \sqrt{(1-f)} & \sqrt{f} \end{bmatrix} \begin{bmatrix} A'_f \\ A'_b \end{bmatrix}.$$

The transmission of this device is intensity dependent. The transmission becomes a maximum when the differential phase between the two counter-propagating fields $|\phi_f - \phi_b|$ is an odd multiple of $\pi$.

3. Proposed scheme

The amplified beat signal from the erbium doped fiber amplifier (EDFA) is passed through an NOLM with a 60:40 coupler to shape it in to a pulse train. The pulse prop-
The beat signal has a frequency of 10 GHz and average power of a few mW around the central wavelength of 1549.72 nm. This beat signal may be amplified to an average value...
of around 300 mW [13]. We have considered an NOLM consisting of SMF of appropriate length for shaping the beat signal instead of using DSF [14]. The effect of dispersion is included in our analysis. This approach has the advantages of compressing the pulses, removing the pedestals and simultaneously increasing the peak power due to the combined effect of chromatic dispersion and optical Kerr nonlinearity.

When a beat signal of peak power 0.5 W is passed through an NOLM consisting of 5.995 km SMF ($\beta_2 = -27.9$ ps$^2$/km), we obtained a pulse train having a FWHM of 4.1 ps with a peak power of 2.25 W. The phase difference between the clockwise and counterclockwise fields was observed to be 0.9 $\pi$, indicating negligible reflected power.

While considering the propagation of the beat signal in the loop, the effect of third order dispersion ($\beta_3$) and Raman self-frequency shift in Eq. (1) have been ignored because of their small contribution for longer pulse durations. For further spectral enrichment, these pulses are subsequently passed through either 8 km of dispersion flattened fiber (DFF) ($\beta_2 = 0.55$ ps$^2$/km) or 900 m DSF ($\beta_2 = -0.55$ ps$^2$/km and $\beta_3 = 0.13$ ps$^3$/km) so as to obtain a 3-dB amplitude spectrum of at least 1600 GHz (Figs. 2a and 2b). To model the propagation of the output of NOLM through DSF and DFF, the Raman self-frequency shift term in Eq. (1) is included. The asymmetry in the output spectrum from DSF as shown in

![Fig. 2. Results of 10 GHz multi-wavelength optical pulse train generation: (a) output spectrum with 8 km DFF as SC fiber, (b) output spectrum with 900 m DSF as SC fiber, (c) variation of peak power as a function of channel wavelength, (d) variation of pulse width across the demultiplexed channels.](image-url)
Fig. 2a is more due to the presence of third order dispersion than Raman self-frequency shift. In contrast, the output spectrum of DFF is symmetric because the third order dispersion is absent and the Raman self-frequency shift is not significant since the pulse is broadened due to the combined effect of normal dispersion and optical nonlinearity. The output spectrum in both the cases is sliced using a 1 × 16 WDM DEMUX having a gaussian profile with bandwidth of 0.33 nm and central wavelengths apart by 100 GHz. In the case of DFF with positive GVD parameter, although the length required is relatively larger, the resultant spectrum is comparatively flat due to the optical wave breaking phenomena [11]. This results in smaller peak power variation (around 8 dB m) across the 16 demultiplexed channels as shown in Fig. 2c. In the case of DSF, power variation is nearly the same as in DFF but it is uneven due to the asymmetric nature of the spectrum (Fig. 2c). Moreover, power is almost constant for the 8 central channels in the case of DFF. Our analysis shows that increasing the length of DFF can increase the number of channels with constant power. In both the cases, the pulse width in different channels is observed to be 13 ps with the exception of one or two central channels where it is slightly larger (Fig. 2d) which can be attributed to the distortion in the central part of the spectrum. This distortion, we believe, is due to the nature of the chirp acquired by the output pulse.

In both the cases, the pulse shapes were observed to be very clean without any pedestals having a period-to-duration ratio of approximately 8:1 except for the central two channels where the base is broad in the case of DFF and there are small pedestals in the case of DSF. The pulse shapes of two consecutive channels (channel code 37 and 36 in ITU-T DWDM grid), in the case of DFF as a SC fiber, are shown in Fig. 3a. It can be observed from Fig. 3a that there is a time de-synchronization in addition to the small peak power variation between the two consecutive pulse trains. We define de-synchronization as the difference between the time slot of a particular channel to the time slot at which the channel would have appeared without any chirping. We call it a positive de-synchronization if the channel appears at a later time slot and negative if it appears at an earlier time slot. This de-synchronization across the demultiplexed channels is due to the nature of the chirp acquired by the output pulse. In the case of DFF as the SC fiber, the chirp acquired is linear, positive and increases in proportion to the length of DFF. The positive chirp here means that the instantaneous frequency increases with the increase in time, i.e., from leading edge to trailing edge of the pulse. Thus we can say that the lower frequency (or higher wavelength) channel should appear before in time as compared to the higher frequency (or lower wavelength) channel. This fact is evident from Fig. 3a, where the higher wavelength channel at 1548.52 nm appears at an earlier time slot as compared to the lower wavelength channel at 1547.72 nm. The variation of de-synchronization as a function of channel wavelength is shown in Fig. 3b. It is obvious from this figure that using 8 km DFF as a SC fiber results in larger de-synchronization (±20 ps) but lesser power variation across the channels. One more noteworthy feature is the smaller but random de-synchronization for DSF, which is due to the random nature of the chirp that is very difficult to compensate for. On the contrary, the nature of the chirp is linear and positive in the case of 8 km DFF, which suggests the possibility of compensating it with a small length of SMF. In fact, our numerical calculations reveal that ~160 m length of SMF can compensate this chirp and all the channels can be synchronized except the central two channels. This is due to the fact that the compensated pulse contains pedestals having central frequency components.
due to the nature of the chirp. In the case of DSF, this type of chirp compensation is not at all possible due to the random nature of the chirp.

This scheme can provide an optical pulse train at 10 GHz rep-rate at a minimum of 16 different optical wavelengths separated by 100 GHz in ITU-T DWDM grid (channel code 42 to 27). This source will be suitable for synchronous data transfer at $16 \times 10 \text{ Gbps}$ in applications such as BP-WDM.

3.2. Scheme for generating multi-wavelength CW output with precise 40 GHz spacing

In this case, we consider a beat signal at 40 GHz frequency amplified to a level of 300 mW (average). For pulse compression and removal of pedestals, a loop consisting of 9 km DSF is more appropriate resulting in a pulse train of FWHM of 1.0 ps with peak power of 1.3 W. Here the phase difference between the counter-propagating fields is $\pi$, resulting in negligible reflected power. The 3-dB bandwidth of output spectrum is observed to be more than 480 GHz as shown in Fig. 4a. In this case the effect of $\beta_3$ and Raman self-frequency shift are taken into account while modeling the pulse propagation through NOLM because of the use of DSF and also because the output pulse is shorter in duration. Due to this reason a slight asymmetry in the output spectrum can be observed in Fig. 4a. If
Fig. 4. Results of multi-wavelength CW output generation: (a) output spectrum after NOLM, (b) output spectrum with 8 km DFF as SC fiber, (c) variation of average power as a function of channel wavelength with and without the inclusion of DFF.
the output of NOLM is further passed through 8 km of DFF, a wider and flatter spectrum is obtained (Fig. 4b). In this case the output power demultiplexed from a AWG DEMUX is observed to be almost constant (∼5 dB m) across the channels as seen in Fig. 4c. It is also possible to slice the central 16 individual components of the output spectrum from NOLM itself using a narrow band 40 GHz spaced AWG DEMUX to get 16 CW channels suitable for modulation at 10 Gbps each. But in that case, the variation in the average power between the 16 channels will be large (nearly 16 dB m) as shown in Fig. 4c. Thus from these calculations, we have verified that 16 CW channels (separated by 40 GHz) with negligible power variation are possible. These will be suitable for both synchronous and asynchronous data transfer at 16 × 10 Gbps.

In the numerical results presented here, the effect of amplified spontaneous emission (ASE) noise coming from the EDFA has been ignored. Earlier, researchers have reported that the presence of noise would lead to a coherence degradation and random fluctuation in each wavelength channel [7,9,10]. However, it has been found that these fluctuations are reduced to a great extent when a DFF with a very small normal dispersion is used [9]. In our work the main reason behind ignoring the ASE noise is the use of NOLM in both the combinations discussed above. The NOLM, with its intensity dependent transmission, reflects the low-power ASE noise more than the signal at a higher power, if the loop length is optimized for the peak power of the signal [15].

4. Conclusion

This paper discusses the modeling of a short pulse-width, high rep-rate, multi-wavelength spread-spectrum source without the use of mode-locking. In the proposed scheme for synchronous data transfer at 16 × 10 Gbps, the pulse width variation is observed to be negligible across all the 16 channels. The peak power in individual channels is found to be sufficient for direct modulation without further amplification. In the case of DFF as a SC fiber, the power variation across the channels is observed to be small but de-synchronization is more, which suggests the need for compensating the chirp prior to demultiplexing. In the scheme where at least 16 CW channels are generated with exact spacing of 40 GHz, the average power in the individual channels is found to be nearly constant. This scheme is also suitable for asynchronous data transfer.

References


