An optical multi-wavelength conversion method for distributed satellite system based on the nonlinearity of SOAs

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Abstract. It is highly necessary to share information between satellites in optics distributed satellite system. The signals usually need to be multi-casted to several nodes. The initial signals can be copied to several wavelengths directly by multi-wavelength converting technology. So it is an efficient way to solve the issue of optics multicast in distributed satellite network. To realize the optics multicast in distributed satellite system, an optical multi-wavelength conversion method based on the nonlinearity of semiconductor optical amplifier (SOA) is put forward. Firstly, by making use of the SOA’s property of spectrum broadening combined with offset filter, the initial signal is filtered by blue-shifted filter and red-shifted. The pre-conversion and detecting signals are produced respectively. Then the multi-wavelength conversion is realized based on the four-wave mixing (FWM) in another SOA. As is obtained by dividing the initial signals, the pre-conversion and detecting signals can be synchronized more easily. The results show that the output Q factor for each channel is promoted and varies with wavelength and signal input power. The power improvement is more than 15dB and the maximum value is 27dB.

1. Introduction
Recently, the distributed small satellite system has attracted much focus. In this system, the multicast technology is quite necessary, which is due to the two reasons. Firstly, lots of missions, such as co-observation, stereo imaging, and the formation keeping, must be accomplished by the collaboration among multiple small satellites, and during the process, much corporate information should be shared by the collaborative satellites [1~4]. Second, some satellites detected data or the data for communication may also need to be transmitted synchronously to different locations. The optical multi-wavelength conversion can replicate the data on one wavelength to several other wavelengths in the optical domain and is one of the most direct and effective methods to solve the problem above [5~7].

Up to now, various schemes of multi-wavelength conversion have been reported, in which the generation of detecting lights is a basic issue. Paper [8] uses spectra slicing on the pulse broadened by fiber to provide a set of detecting signals. The scheme can offer the relatively flat and wide detecting light, but its high power consumption and requirements of long fiber are unsuitable for satellite applications. Papers [9] [10] [11] use several separated lasers as detecting lights, which may bring a better quality of converted signals, but the volume and the cost of system also increase. For example, eight lasers are employed in [11]. To solve the problem, paper [12] replaces the multiple lasers by one
multi-wavelength laser. However, the synchronization between signal and detecting pulses is needed, especially for the bit rate more than 10Gb/s.

In this paper, a multi-wavelength conversion scheme for distributed satellite system based on the nonlinearity of SOAs is put forward. The scheme utilizes SOA’s property of spectrum broadening combined with offset filter to get the pre-conversion and detecting signals, which can not only solve the problem of synchronization between signal and detecting pulses, but also improve the quality of signals.

2. Principles
The principle of the multi-wavelength conversion is shown in Fig.1. It includes a pre-conversion part and a conversion part. In pre-conversion part, the signal with wavelength $\lambda_0$ is sent into SOA1, which is set to have a short carrier recovery time, and as a result, the spectrum of signal will be broadened to the two sides. The output is divided into two portions: through the optical band-pass filter (OBPF1), the high-frequency part is selected as the pre-conversion signal; the other part first passing through OBPF2 to select the low-frequency part, then broadened again by SOA2 and finally suffers a spectrum slicing by optical comb filter (OCF). In conversion part, taking the output of the two portions respectively as the signal and detecting light, the multi-wavelength conversion is realized based on the FWM in SOA3. The optical delay line (ODL) is used to compensate for the time warp caused by the offset filter. The array waveguide grating (AWG) can separate the converted signals of different wavelengths.

2.1. Pre-conversion part
In the pre-conversion part, the main functions are realized by the use of SOA combined with offset filter, which can not only offer an optical amplification but also improve the quality of signals. The detailed properties are extremely relevant to the relationship between the pulse width and the carrier recovery time.

Ignoring the internal loss of SOA, the power and the phase shift of signal after passing through SOA can be given by

$$ P_{\text{out}}(\tau) = P_{\text{in}}(\tau) \exp[h(\tau)] $$

$$ \phi(\tau) = -\frac{1}{2} \alpha h(\tau) $$

Where $P_{\text{in}}(\tau)$ and $P_{\text{out}}(\tau)$ are the input and output power of the pulse, $\phi(\tau)$ is the phase shift induced by SPM, $\alpha$ is linewidth enhancement factor, $h(\tau) = \int g(z, \tau) dz$ represents the integrated gain at each point of the pulse profile. According to the paper [13], $h(\tau)$ is the solution of the following ordinary differential equation:

$$ \frac{dh(\tau)}{d\tau} = \frac{g_0 L - h(\tau)}{\tau_c} - \frac{P_{\text{in}}(\tau)}{E_{\text{sat}}} \left[ \exp(h(\tau)) - 1 \right] $$

Where $g_0$ is the small-signal gain, $L$ is the length of SOA, $\tau_c$ is the carrier recovery time, $E_{\text{sat}}$ is the saturation energy.
If the full width at half maximum (FWHM) of input pulse \( \tau_p \) is much smaller than \( \tau_c \), the first term on the right-hand of (3) can be neglected. Physically, this neglect can be account for assuming that the pulse is so short that the gain has no time to recover. In this limit \( \tau_p / \tau_c << 1 \), the solution of (3) is

\[
h(\tau) = -\ln\left[ 1 - \frac{1}{\exp(g_s L)} \exp\left( \frac{U_{\text{in}}(\tau)}{E_{\text{sat}}} \right) \right]
\]  

(4)

Where \( U_{\text{in}}(\tau) \) is the fraction of the pulse energy contained in the leading part of the pulse up to \( \tau' \leq \tau \).

Using the equation \( \Delta \nu = \frac{-1}{\tau^2} \) together with (1) ~ (4), the chirp induced by SPM can be obtained by

\[
\Delta \nu(\tau) = -\frac{\alpha(G_0 - 1)}{4\pi G_0} \frac{P_{\text{sat}}(\tau)}{E_{\text{sat}}} \exp\left( \frac{U_{\text{in}}(\tau)}{E_{\text{sat}}} \right)
\]  

(5)

Where \( G_0 = \exp(g_0 L) \) is the unsaturated single-pass amplifier gain. It can be found from (5) that SOA induced chirp is always negative as usually \( G_0 > 1 \).

However, if \( \tau_c \) is comparable to \( \tau_p \), the result will be more different. Consider \( \tau_p / \tau_c >> 1 \), and by ignoring the time derivative in (3), the implicit solution of \( h(\tau) \) can be written as

\[
h(\tau) = g_s L - \frac{P_{\text{sat}}(\tau)}{P_{\text{sat}}} \left[ \exp(h(\tau)) - 1 \right]
\]  

(6)

Where \( P_{\text{sat}} = E_{\text{sat}} / \tau_c \) is the saturated power. If we substitute (6) in (2) and neglect the constant phase shift, the SOA induced nonlinear phase shift can be obtained by using (1)

\[
\phi_{\text{out}}(\tau) = \frac{\alpha}{2} \frac{P_{\text{sat}}(\tau) - P_{\text{in}}(\tau)}{P_{\text{sat}}}
\]  

(7)

Usually, for high-gain condition \( P_{\text{in}}(\tau) << P_{\text{sat}}(\tau) \), and the chirp can be approximately given by

\[
\Delta \nu = \frac{\alpha}{2P_{\text{sat}}} \frac{\partial P_{\text{sat}}(\tau)}{\partial \tau}
\]  

(8)

Different from (5), the chirp described by (8) contains both negative and positive compositions respectively at the front edge and back edge of pulse. It is worth notice that the maximum values of chirp for both cases are near the peak of the output pulses and there is little chirp near the bottom of pulses.

Fig.2 shows the influence of carrier recovery time on the waveform and the spectrum of the output pulse. In the simulation, we use the SOA with \( G_0 = 30 \)dB and the Gaussian pulse with FWHM of 30ps. For \( \tau_p / \tau_c = 0.05 \), as the carriers cannot recover in time at the back edge of pulse, the pulse waveform inclines seriously toward the front edge. For \( \tau_p / \tau_c = 1 \), the waveform is broader as its trailing side becomes more intense. This is because the carriers have time to recover partially when the trailing edge arrives. With the decrease of \( \tau_c \), the output pulse is much broader and less asymmetric, which is more obvious \( \tau_p / \tau_c = 3 \). The corresponding output spectra are shown in fig.2(b). As \( \tau_c \) becomes shorter, the spectral shift towards low frequency (red-shifted side) becomes smaller and the spectrum is less asymmetric. Meanwhile, the sideband on the high frequency (blue-shifted side) becomes more intense. For \( \tau_p / \tau_c = 3 \), the amount of frequency components of the blue-shift side is almost comparable to that of the red-shift side.
According to the analysis above, if the carrier recovery time of SOA1 is small enough then the pulse width, the spectrum of the output pulse will be broadened to the two sides. When it passes through the OBPF1 and OBPF2, whose central frequencies are equal to values at the two peaks of pulse spectrum, the part of pulse near the bottom which has little frequency shift will attenuate more seriously than the part near the peak. As the bottom of pulse contains mainly noise, the optical signal noise ratio (OSNR) after the OBPF1 and OBPF2 will improve evidently. The carrier recovery time of SOA2 is set to be longer than the pulse width. As a result, the spectrum will be broadened only to the low frequency. Then by using the comb filter, a set of red-shifted detecting signals with equal frequency intervals will be selected.

2.2. conversion part

In an SOA, the FWM efficiency mainly depends on the gain, which, in turn, saturates at high pump intensity. As a result, gain saturation sets a limitation to the maximum attainable FWM efficiency. To eliminate this limitation, one effective method is using a certain class of short pulses. For short pulses, the gain can operate in a transient mode so that the FWM process may take place with high intensity and meanwhile keep an unsaturated large gain, which, subsequently, brings large efficiency.

According to [14], the conversion efficiency of FWM in an SOA is dependent on the cube of the amplifier gain and the square of the pump power. That is

$$\eta \propto G^3 I_p^2$$

(9)

Where IP is the pump power. The increase of pump power will lead to a saturation of SOA, and subsequently the compression of the gain. Generally, the degree of gain compression is a transcendental function of pump intensity, so by introducing an empirical relationship $G \propto I_p^{-\gamma}$, (9) can be written as

$$\eta \propto I_p^{2-3\gamma}$$

(10)

(10) shows that with the increase of pump power, the conversion efficiency will increase for $\gamma < 2/3$, and decrease for $\gamma > 2/3$.

The noise figure ($NF$) is defined as the ratio of input OSNR to the OSNR of the corresponding wavelength-converted signal. Assuming that the input photon energy $\hbar w$ contains only shot noise and the converted signal contains shot noise and ASE noise of power spectral density $W$ [W/Hz]. Assuming that the change in photon energy between input and output signals is negligible, this ratio can be obtained by

$$NF = \frac{2W + \hbar w}{\hbar w \eta}$$

(11)
In fact, for the continuous-wave (CW) pump, \( \eta \) is often very small, so we can conclude \( NF < 1 \); however, for the pulses pump, a large \( \eta \) of more than 10 dB can be easily achieved, so the increase of output OSNR may also be realized for \( NF > 1 \).

3. Simulation result
The simulation is performed using the setup shown in fig.3. 10Gb/s return-to-zero (RZ) on-off keying (OOK) pseudo-random binary sequence (PRBS) with FWHM of 15ps is produced. The laser operated under CW condition with a wavelength of 1550nm and linewidth of 10MHz. The dashed part is used to add noise to signals, by which the power and OSNR of input signals can be adjusted. OBPF0 with 3dB bandwidth of 40GHz can remove part of out-band noise. OBPF1 is of 30GHz bandwidth and frequency offset is 50GHz higher to 1550nm; OBPF2 is of 30GHz bandwidth and frequency offset is 50GHz lower to 1550nm. The central wavelength of OCF is 1550.4nm with 30GHz bandwidth and 100GHz free spectral range. ODL is set to be 54ps, and the parameters of SOA1, SOA2, and SOA3 are shown in table 1. In the following content, we will take the one-to-six wavelength conversion as an example to analyze the performance of the scheme.

![Figure 3. Setup of the simulation](image)

**Table 1. Parameters of SOA1**

| Name                     | Symb | SOA1   | SOA2   | SOA3   | U   |
|--------------------------|------|--------|--------|--------|-----|
| Injection current        | \( I \) | 0.15   | 0.12   | 0.15   | A   |
| Active region length     | \( L \) | 0.0005 | 0.0005 | 0.0005 | m   |
| Active region width      | \( W \) | \( 3 \times 10^{-7} \) | \( 8 \times 10^{-7} \) | \( 1 \times 10^{-7} \) | m   |
| Active region thickness  | \( d \) | \( 8 \times 10^{-8} \) | \( 8 \times 10^{-8} \) | \( 8 \times 10^{-8} \) | m   |
| Optical confinement      | \( \Gamma \) | 0.5    | 0.5    | 0.5    | m   |
| Differential gain        | \( a \) | \( 2.78 \times 10^{-10} \) | \( 2.78 \times 10^{-10} \) | \( 2.78 \times 10^{-10} \) | m   |
| Carrier density at \( N_0 \) | | \( 1.4 \times 10^{24} \) | \( 1.4 \times 10^{24} \) | \( 1.4 \times 10^{24} \) | m   |
| Recombination \( A \)    | | \( 1.43 \times 10 \) | \( 1.43 \times 10 \) | \( 1.43 \times 10 \) | 1/   |
| Recombination \( B \)    | | \( 1 \times 10^{16} \) | \( 1 \times 10^{16} \) | \( 1 \times 10^{16} \) | m   |
| Recombination \( C \)    | | \( 5 \times 10^{-39} \) | \( 1 \times 10^{-39} \) | \( 5 \times 10^{-39} \) | m   |
| Linewidth enhancement    | \( \alpha \) | 5      | 5      | 5      | 5   |

Fig.4 shows the spectra of signal at different positions. The initial spectrum with central wavelength 1550nm is broadened symmetrically to both sides after the SOA1 and a concavity is formed near the 1550nm. The power is also promoted for approximately 25dB. By the offset filter of OBPF1 and OBPF2, the down-converted and up-converted signal is selected, respectively, at wavelength 1549.6nm and 1550.4nm as shown in fig.4(c) and fig.4(d). Fig.4(e) is the broadened spectrum of up-converted signal by SOA2. It is shown that a flat region for about 200GHz appears mainly on the right of 1550.4nm. In fact, according to the requirement of application, the width of this flat region can be adjusted to a certain extent by changing the parameters of SOA2. Here, two channels with 100GHz space are needed, so the spectrum width is satisfied. This result is shown in fig.4(f). We can see that two peaks are formed at 1550.4nm and 1551.2nm, whose power is 8dB higher than that of the nearby spectral components.
As is pointed out in former content, the scheme can solve the problem of synchronization between the signal and detecting pulses when the separated detecting laser is used. The blue-shifted and red-shifted filtering in the pre-conversion part can also introduce the delay. However, as the delay depends on the size of offset filtering, it is an invariable value. The delays caused by offset filters are shown in Fig.5. fig.5(a), (b) and (c) are respectively the initial pulses and the pulses after OBPF₁, OBPF₂, and (d), (e) is the pulses of wavelength 1551.2nm after OCF and ODL. It is shown that the blue-shifted filtering of OBPF₁ causes a timed departure towards the back edge of pulses and the red-shifted filtering of OBPF₂ causes a departure towards the front edge of pulses, which is more serious after the OCF. Fig.5(e) is the result after compensation by ODL with 0.054ns delay and it is similar to the signal pulses of fig.5(b).

Fig.6 shows the output Q factor of six converted signals for the different input power of -20dBm and -17.5dBm, and the initial input Q factor for the two powers are 5.3 and 6.9. It is can be seen that the Q factor is improved more or less for both cases, which is attributed to the regeneration in the pre-conversion part and the high efficiency of FWM in the conversion part. Additionally, the increase of input power does not cause an evident improvement in the Q factor. This results from the nonlinearity of SOA and the several times of offset filters. When the signals with different power come into SOA₁, the spectrum will be nonlinearly broadened. And after the offset filter, the difference caused by the values of power will be ambiguous. This ambiguousness may further increase after the SOA₂ and OCF, as the property of the latter depends greatly on that of the former.
Power improvement is an important factor for wavelength conversion and is defined as the ratio between output power and input power of the converter, which is different from the conversion efficiency of FWM. Fig. 7 shows the power improvement of the scheme for the input power of -20dBm. As we can see that the power improvement of each converted signal is more than 15dB and can reach a maximum of 27dB, which is mainly attributed to the amplification of SOA. Additionally, the improvements for 1550.4nm and 1551.2nm are larger than that of others.

![Figure 7. The power improvement of wavelength-converted signals](image_url)

### 4. Conclusion
Multi-wavelength conversion is an effective method to realize the multicast on optical domain, which can enhance the flexibility of the optical network. In this paper, a multi-wavelength conversion scheme based on the nonlinearity of SOA is demonstrated. The scheme translates the random timing jitter between signal and detecting pulses into fixed delay, which can be easily compensated by an ODL. Due to the regeneration of SOA combined with offset filter, the Q factor of converted signal for each channel is promoted. The power improvement of output signal to initial signal can reach more than 15dB.

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