An optical regenerative wavelength conversion scheme for satellite based on SPM of SOA and offset filter
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Abstract: An optical regenerative wavelength conversion scheme without separated pump laser is put forward to promote the wavelength utilization ratio in distributed satellite network. The scheme adopts the self-phase modulation (SPM) in semiconductor optical amplifier (SOA) to broaden the signal spectrum toward both higher and lower frequency owing to the property that the time of carrier recover is less than pulsewidth. Then the signal light and pump light are extracted by a high-pass filter and a low-pass filter respectively. Finally, the wavelength conversion is realized based on the four-wave mixing (FWM), where the signal light and pump light are passing through another SOA. The simulation results demonstrate that the conversion efficiency can be more than 15dB, and the Q factor improvement can reach to 4dB when input power is small than -22dBm.

Key words: wavelength conversion, semiconductor optical amplifier, self-phase modulation, four-wave mixing

1 Introduction

The distributed satellite system based on optical link can provide multiple baseline combinations and shows strong survivability and maneuverability. Meanwhile, the high data rate and wide bandwidth can satisfy the various requirements of space mission in the future\[^{[1\sim3]}\]. However, as the information exchanging is frequent and available bandwidth is limited in distributed satellite system, wavelength conversion is necessary to promote the wavelength utilization efficiency and relieve the congestion\[^{[4\sim6]}\].

Although the principle of wavelength conversion on satellite is the same with that in terrestrial network, some special requirements\[^{[7\sim8]}\] are demanded due to the limitation on payload, the low optical power and the long distance between satellites. So far, most wavelength conversion schemes need separated detecting laser, which increases the complexity and the cost of system seriously\[^{[9\sim11]}\], especially for the large number of wavelength channels. The wavelength conversion scheme based on spectrum slice of amplified spontaneous emission (ASE) noise can omit the detecting laser\[^{[12\sim14]}\], however the coherence of ASE noise is poor, so the transmission distance is limited. The paper \[^{[15]}\] makes use of a single SOA to realize the conversion of two signals synchronously, which uses one of the signals as detecting light and simplifies the system. However, the scheme has strict limitations on the format of signal, so it is not applicable to the general cases.

In this paper, an optical regenerative wavelength conversion scheme without separated pump laser for distributed satellite network is put forward. The scheme makes use of an SOA accompanied with two offset filters to produce the pump and signal lights, and then the wavelength conversion is realized in another SOA based on FWM. As much of amplitude noise can be removed through the SOA with offset filter, the scheme would also give regeneration to the signal.

2 Principle of operation

The principle of the wavelength conversion scheme is presented in Fig.1. It includes a pre-conversion part and a conversion part. In pre-conversion part, the signal with wavelength $\lambda_0$ is first transmitted into SOA1, and as a result of SPM, the spectrum will be broadened toward both the high- and low-frequent sides. The output signal is divided into two portions, one passing through the high-pass filter OBPF1, the other passing through the low-pass filter OBPF2, and
subsequently the signals with wavelength $\lambda_1$ and $\lambda_2$ are extracted. In conversion part, the wavelength conversion is realized based on the FWM in SOA$_2$ by taking $\lambda_1$ signal as the signal light and $\lambda_2$ signal as the pump light. The optical band-pass filter (OBPF$_3$) is finally used to filter out the converted signal. The polarization controller (PC) can keep the polarization direction of signal and pump the same.

Fig.1 Principle of wavelength conversion scheme

2.1 The pre-conversion part

Ignoring the internal loss, when the signal passes through SOA, the output power, the phase shift and the gain can be given by

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

(1)

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

(2)

$$\frac{\partial g(z, \tau)}{\partial \tau} = \frac{g_0 - g(z, \tau)}{\tau_c} - \frac{g(z, \tau)P}{E_{\text{sat}}}$$

(3)

Where $P_{\text{in}}(\tau)$ and $P_{\text{out}}(\tau)$ are the input and output power, $\phi(\tau)$ is phase shift induced by SPM, $\alpha$ is linewidth enhancement factor. $h(\tau) = \int_0^L g(z, \tau)dz$ represents the integrated gain at each point of the pulse profiles, $g(z, \tau)$ is the signal gain, $L$ is the active region length. $g_0$, $\tau_c$, $E_{\text{sat}}$ are small-signal gain, carrier recovery time (CRT), saturation energy and they are defined as

$$g_0 = \Gamma a N_0 (1/I_0 - 1)$$

(4)

$$\tau_c = \frac{1}{A + BN + CN^2}$$

(5)

$$E_{\text{sat}} = h\nu_0 wd / \Gamma a$$

(6)

Where $\Gamma$ is optical confinement factor, $a$ is differential gain, $N_0$ is carrier density at transparency, $I$ is injection current, $I_0 = qVN_0 / \tau_c$ is the current required for transparency, $q$ is electron charge, $V$ is active volume. $A$, $B$ and $C$ are related to recombination constants, $N$ is carrier density, $h\nu_0$ is the photon energy.

If we integrate (3) over the amplifier length, $h(\tau)$ will be the solution of the following ordinary differential equation:

$$\frac{dh(\tau)}{d\tau} = \frac{g_0L - h(\tau)}{\tau_c} - \frac{P_{\text{in}}(\tau)}{E_{\text{sat}}} \left[\exp(h(\tau)) - 1\right]$$

(7)

If the input pulse width $\tau_p$ is much smaller than CRT, the first term on the right-hand of (7) 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 \( \frac{\tau_p}{\tau_c} << 1 \), the solution of (7) is

\[
h(\tau) = -\ln \left[ 1 - \left( 1 - \frac{1}{\exp(g_0 L)} \right) \exp \left( -\frac{U_{in}(\tau)}{E_{sat}} \right) \right]
\]

(8)

Where \( U_{in}(\tau) \) is the fraction of the pulse energy contained in the leading part of the pulse up to \( \tau' \leq \tau \). It can be obtained by

\[
U_{in}(\tau) = \frac{1}{2} E_{in}[1 + \text{erf}(\tau / \tau_o)]
\]

(9)

Where \( E_{in} \) is the input pulse energy, \( \tau_0 \) is related to the full width at half maximum (FWHM) by \( \tau_p \approx 1.665 \tau_0 \). Using the equation \( \Delta v(\tau) = -\frac{1}{2\pi} \frac{\partial \phi}{\partial \tau} \) together with (1) ~ (9), the chirp induced by SPM can be obtained by

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

(10)

Where \( G_0 = \exp(g_0 L) \) is the unsaturated single-pass amplifier gain. As usually \( G_0 > 1 \), (10) indicates that SOA induced chirp is always negative.

For the contents above, we consider the case of \( \frac{\tau_p}{\tau_c} << 1 \). However, if \( \tau_c \) is comparable to or even smaller than \( \tau_p \), the result will be more different. Consider the condition \( \frac{\tau_p}{\tau_c} >> 1 \), and by neglecting the time derivative in (7), the implicit solution of \( h(\tau) \) can be written as

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

(11)

Where \( P_{sat} = E_{sat} / \tau_c \) is the saturated power.

If we substitute (11) in (2) and neglect the constant phase shift, the SOA induced nonlinear phase shift can be obtained by using (1)

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

(12)

Usually, \( P_{in}(\tau) << P_{sat}(\tau) \) is satisfied for high-gain condition, so the chirp can be approximately written as

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

(13)

Different from the case of (10), the chirp described by (13) contains both negative and positive portion respectively at front edge and back edge of pulses.

Fig.2 shows the influence of CRT on the shape and the spectrum of output pulses. In the simulation, the SOA with \( G_0=30\text{dB} \) and un-chirped Gaussian pulse with FWHM of 30ps are used. For \( \frac{\tau_p}{\tau_c} = 0.05 \), the pulse shape inclines evidently toward the front edge because the carriers
can not recover in time at the back edge of pulse. For \( \tau_p / \tau_c = 1 \), the output pulse becomes broader as its trailing side becomes more intense. This can be explained by noting that the carriers have time to recover partially when the trailing edge arrives. As \( \tau_p / \tau_c \) increases, the output pulse is much broader and less asymmetric. These properties are more obvious for \( \tau_p / \tau_c = 3 \). The output spectra corresponding to the pulse shapes are shown in fig. 2(b). With the increase of \( \tau_p / \tau_c \), 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 on blue-shift side is almost comparable to that on red-shift side.

![Graphs showing pulse shapes and spectra](image)

(a) The shape of output pulses  
(b) the spectrum of output pulses

Fig.2 Effect of CRT on the shape and the spectrum of output pulses

Based on the analysis above, if a red- or blue-shifted filtering is imposed on the pulses amplified by SOA with smaller CRT than pulsewidth, a red- or blue-shifted signal will be extracted respectively. Meanwhile, the part near the peak power with a larger chirp will suffer a slight attenuation and the part with lower power with a little chirp will attenuate severely. As the low-power part contains mainly noise, the optical signal noise ratio (OSNR) of the red- and blue-shifted signals also improve.

2.2 The conversion part

When the signal and pump lights with frequencies \( w_0 \) and \( w_1 \) transmit into SOA, due to the FWM, carriers in the active region will form a grating that correlates with the intensity of input signals. Influenced by the grating, the pump light is scattered to produce a conjugate light with a new frequency of \( w_2 = w_1 + \Delta w \) and the signal light is scattered to produce an accompany light with a frequency of \( w' = w_0 - \Delta w \), as shown in fig. 3. Both the conjugate and accompany lights carry the information of the signal, including the intensity and phase information.
Assume that the slowly varying amplitudes of signal and pump lights in SOA2 are \( E_0(z, \tau), E_1(z, \tau) \) and the total slowly varying amplitude in the SOA2 can be written as

\[
E(z, \tau) = E_0(z, \tau) + E_1(z, \tau)e^{-i\Delta\omega \tau} + E_2(z, \tau)e^{i\Delta\omega \tau}
\]

(14)

Where \( E_2(z, \tau) \) represents the slowly varying amplitude of conjugate light. In (14), the contribution of accompany light is ignored, as its power is usually much lower than the conjugate light. If the cross-gain modulation, gain dispersion and internal loss are neglected, the transmission of pump, signal and conjugate lights will satisfy the following equations:

\[
\frac{\partial E_j(z, \tau)}{\partial z} = \frac{g_j'(z, \tau)}{2}(1 - i\alpha')E_j(z, \tau), \quad j = 0,1
\]

(15)

\[
\frac{\partial E_2(z, \tau)}{\partial z} = \frac{g_2'(z, \tau)}{2}(1 - i\alpha')E_2(z, \tau) - \frac{g_1'(z, \tau)}{2}\mu E_0^2(z, \tau)E_1^*(z, \tau)
\]

(16)

Where \( g_j(z, \tau), \alpha' \) are the gain and the linewidth enhancement factor of SOA2. The coupling coefficient \( \mu \) comes from the contributions of three factors: carrier density pulsation (CDP), carrier heating (CH), spectral-hole burning (SHB), and can be written as

\[
\mu = \mu_{CDP} + \mu_{CH} + \mu_{SHB}
\]

(17)

\[
\mu_{CDP} = \varepsilon_{CDP} \frac{1 - i\alpha'}{(1 + i\Delta w_\tau)(1 + i\Delta w_{\tau_1})}
\]

(18)

\[
\mu_{CH} = \varepsilon_{CH} \frac{1 - i\alpha'}{(1 + i\Delta w_{\tau_1})(1 + i\Delta w_{\tau_1})}
\]

(19)

\[
\mu_{SHB} = \varepsilon_{SHB} \frac{1 - i\alpha_{SHB}}{1 + i\Delta w_{\tau_1}}
\]

(20)

Where \( \varepsilon_{CDP} \) is the coefficient of carrier density pulsation, \( \varepsilon_{CH} \) and \( \varepsilon_{SHB} \) are the nonlinear gain compression factors due to CH and SHB, \( \alpha_{CH} \) and \( \alpha_{SHB} \) are the linewidth enhancement factors corresponding to CH and SHB, \( \tau_1 \) and \( \tau_h \) are the carrier-carrier scattering time and carrier-photon scattering time.

Then integrating (15) and (16) over the amplifier length, we can obtain

\[
E_j(L', \tau) = E_j(0, \tau)e^{(1 - i\alpha')h'/2}, \quad j = 0,1
\]

(21)

\[
E_2(L', \tau) = -\frac{1}{2}\mu e^{-h'}(e^{h'} - 1)E_0^2(L', \tau)E_1^*(L', \tau)
\]

(22)

Where \( L' \) and \( h' \) are the length and integrated gain of SOA2.

The conversion efficiency is a critical figure of merit for wavelength convertors, and it can be
defined as

\[ \eta = \frac{|E_2(L)|^2}{|E_0(0)|^2} \]  \hspace{1cm} (23)

Where \( |E_2(L)|^2 \) is the output power of convertor and \( |E_0(0)|^2 \) is the input signal power. It is noticed that the conversion efficiency here is the ratio of output power to input power of convertor, but not the conversion efficiency of FWM.

In fact, the power of conjugate and accompany lights are related with several factors, such as the power of signal and pump lights, the saturation performance of SOA. In many studies, accompany light is also used as converted signal. In the following part, we will take conjugate light and accompany light as the up- and down-conversion signals to analyze the properties of the scheme.

3 Numerical results and discussion

The simulation is performed using the setup shown in fig.4. 10Gb/s return-to-zero (RZ) on-off keying (OOK) pseudo-random binary sequence (PRBS) with FWHM of 15ps is produced and the length of PRBS is \( 2^{12}-1 \). The laser operated under continuous wave (CW) condition with the wavelength of 1550nm and the linewidth of 10MHz. The dashed part is used to manufacture some noise to the signal, by which the power and OSNR can also be adjusted. OBPF\( _0 \) can remove part of out-band noise, whose center wavelength is the same with the laser and 3dB bandwidth is 40GHz. The 3dB bandwidths of both OBPF\( _1 \) and OBPF\( _2 \) are 30GHz, whose frequency shifts are 50GHz higher and lower to 1550nm respectively; the wavelength of OBPF\( _3 \) is adjustable and the bandwidth is 30GHz; parameters of SOA\( _1 \) and SOA\( _2 \) are shown in table 1. BER analyzer is used to observe the performance of the convertor.

![Fig.4 The setup of simulation](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>SOA( _1 )</th>
<th>SOA( _2 )</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection current</td>
<td>( I )</td>
<td>150</td>
<td>180</td>
<td>mA</td>
</tr>
<tr>
<td>Active region length</td>
<td>( L )</td>
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<td>0.0005</td>
<td>m</td>
</tr>
<tr>
<td>Active region width</td>
<td>( W )</td>
<td>1e-007</td>
<td>5e-007</td>
<td>m</td>
</tr>
<tr>
<td>Active region thickness</td>
<td>( d )</td>
<td>8e-008</td>
<td>8e-008</td>
<td>m</td>
</tr>
<tr>
<td>Optical confinement factor</td>
<td>( \Gamma )</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Differential gain</td>
<td>( A )</td>
<td>2.78e-020</td>
<td>2.78e-020</td>
<td>m(^2)</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>( A )</td>
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<td>1.43e+008</td>
<td>1/s</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>( B )</td>
<td>1e-016</td>
<td>1e-016</td>
<td>m(^3)/s</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>( C )</td>
<td>5e-039</td>
<td>3e-039</td>
<td>m(^6)/s</td>
</tr>
<tr>
<td>Linewidth enhancement factor</td>
<td>( \alpha )</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Initial carrier density</td>
<td>( N' )</td>
<td>3e+024</td>
<td>3e+024</td>
<td>1/m(^3)</td>
</tr>
</tbody>
</table>

Fig.5 shows the spectra of signals after different components. In the simulation, the conversion from 1550nm (fig.5(a)) to 1548.8nm (fig. 5(f)) is taken as an example. From fig.5(b), it can be seen that the spectrum is broadened toward both lower and higher frequency about 50GHz and the signal power is also amplified. After the offset filtering of OBPF\( _1 \) and OBPF\( _2 \), a high-frequency signal and a low-frequency signal are extracted respectively. After the effect of FWM in SOA\( _2 \), the new frequency components appear evidently at about 1548nm and 1551.2nm.
As shown in fig.5(f), the final signal with center wavelength 1548nm is obtained by the selection of OBPF3.

Fig. 5 The spectra at different points

Fig.6 shows the eye height improvement versus input OSNR after OBPF1 and OBPF2 in wavelength pre-conversion part. It depicts that the eye height decreases with the increase of OSNR for both cases. This is because that the proportion of noise in signals with lower OSNR is larger than that with higher OSNR and as a result, the more noise will be removed when passing through the offset filter.

Fig.7 exhibits the Q factor improvement versus input power. The power entering the SOA2 during the simulation is about 4dBm. The result shows that the Q factor is promoted for both up- and down-conversion and the improvement for down-conversion is larger than that of up-conversion. The improvement decreases with the growth of input power, which can be explained conforming with the result in fig.6. Compared with the initial eye diagram, the noise at the bottom of signals at points (A) and (B) is suppressed evidently and the eye height increases. Fig.8 is the BER properties. We can see that the BER of conversion signal decreases evidently, which is consistent with the results of fig.7.
Fig. 7 Q factor improvement versus input power

Fig. 9 shows the Q factor improvement versus input power for different length of PRBS. It can be seen that the Q factor improvement lightly decreases as the \( L_{PRBS} \) increases from \( 2^{12}-1 \) to \( 2^{18}-1 \). This phenomenon is a little obvious for lower input power, but for the higher input power the changing of \( L_{PRBS} \) shows negligible influence on the Q factor improvement. The result indicates that the performance of the scheme is nearly steady for different length of PRBS.

Fig. 10 is the Q factor improvement versus frequency difference for both wavelength up- and down-conversion and the input power is -20dBm during the simulation. It shows that the Q factor improvement of down-conversion is larger than that of up-conversion when the frequency difference is smaller than 220GHz. However, the result turns out to be just opposite as the frequency difference is larger than 220GHz. Anyhow, the increase of frequency difference will finally lead to a decrease of Q factor for both the up- and down-conversion. The spectral ranges allowing of regeneration for wavelength up-conversion and down-conversion are 280GHz and 250GHz respectively, beyond which the wavelength conversion will lead to a decrease of Q factor.

Fig. 11 plots the conversion efficiency versus input power. From the figure, the conversion
efficiency of up-conversion is larger than that of the down-conversion, which can be attributed to character that the conjugate light in FWM is larger than the accompany light. As shown in fig.5, the power at 1550.4nm after OBPF$_1$ is obviously larger than that at 1549.6nm after OBPF$_2$. Accordingly, the light of 1550.4nm is considered as pump light and the signal of 1551.2nm is the conjugate light even although both the two lights contain the signal information. It should be noticed that the conversion efficiency here is defined as equation (23), which is not the conversion efficiency of FWM in SOA$_2$.

![Conversion efficiency versus input power](image)

Fig.11 Conversion efficiency versus input power

As the scheme is proposed to be applied in satellite system, there are three advantages compared with other schemes. Firstly, catering for the limited payload on satellite, the scheme is of simple structure and small volume. So far, most of wavelength conversion schemes use several separated lasers as detecting lights\[^9\]-\[^11\], e. g. eight lasers are employed in the scheme reported by G. Contestabile\[^11\], which may promote the quality of converted signals, but the volume and the cost of system also increases. Although the several lasers can be substituted by a tunable laser, the control is still complex in practice. In our proposed scheme, the input signal with certain power range can provide a fixed wavelength up- or down-conversion, which is much more attractive for the network with large number of wavelength channels. Secondly, the wavelength-converted signal is amplified and regenerated, which can compensate the injury caused by the noise and long-distance transmission. The scheme based on spectrum slice of ASE noise can omit the detecting laser\[^14\]-\[^15\], but the coherence of ASE noise is poor, so the transmission distance in space is much limited. Finally, as the key component of the scheme, SOA has the mature technology and is easy to be integrated, which is of great advantages in space application.

The carrier recovery time of the SOA$_1$ in the scheme is calculated to be about 22ps. The SOA with similar characteristics has been reported in paper [16] and the doctoral dissertation [17], where the gain recovery time are respectively 70ps and 25ps. Additionally, the structure of offset filtering and the wavelength conversion based on FWM is also convenient to be realized. Combining with discussion above, the proposed scheme in this manuscript is technically feasible.

4 Conclusion

In order to promote the wavelength utilization ratio in distributed satellite network, an optical regenerative wavelength conversion scheme without separated pump laser is demonstrated. The detailed operation principle is analyzed and the spectrum conversion process is shown. The results show that the scheme can suppress the amplitude noise effectively and the Q factor improvement of converted signal can reach to 6dB for both up- and down-conversion; the conversion efficiency can be more than 15dB. Owning to the simple structure, along with small volume and mature technology of SOA, the scheme shows great potential for application in distributed satellite
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References