5

The Application of SOA in All-optical Wavelength Conversion and ROF System

Lin Chen, Jianjun Yu, Jia Lu, Hui Zhou and Fan Li
Hunan University,
China

1. Introduction

Wavelength conversion has been suggested as one of the key functions for wavelength-division-multiplexing (WDM) optical networks and photonic switch blocks. Several methods, such as a self-phase modulation (SPM), a cross-gain modulation (XGM), and cross-phase modulation (XPM), can be used to realize all optical wavelength conversion (AOWC) [1-29]. However, four-wave mixing (FWM) based on nonlinear media, such as optical fiber and semiconductor optical amplifier (SOA), is considered to be the most promising scheme because it is fully transparent to the signal bit rate and modulation format. AOWC in SOA has many advantages such as easily compatible and highly covert efficiency. AOWC based on FWM in SOA for regular signal such as ON/OFF keying (OOK) signal has already investigated maturely but not for OFDM signals.

This chapter discusses the performance for OFDM signal in AOWC based on FWM in an SOA. We found the result for OFDM signal is the same as that of OOK signal. Multiple frequency mm-wave generation is one of the key techniques in radio over fiber (ROF) system. Many methods can generate multiple frequency mm-wave such as using optical carrier suppression (OCS), suppression of odd-order sidebands, multi-cascaded external modulators and so on. Some references have proposed that multiple frequency mm-wave can be generated by using SOA based on FWM effect and discuss polarization insensitive in SOA. This chapter also introduces this method to generate mm-wave and discusses the polarization insensitive all-optical up-conversion for ROF system based on FWM in a SOA. We have proposed and experimentally investigated polarization insensitive all-optical up-conversion for ROF system based on FWM in a SOA. One method is that a parallel pump is generated based on odd-order optical sidebands and carrier suppression using an external intensity modulator and a cascaded optical filter. Therefore, the two pumps are always parallel and phase locked, which makes the system polarization insensitive. This scheme has some unique advantages such as polarization insensitive, high wavelength stability, and low-frequency bandwidth requirement for RF signal and optical components. The other method is where co-polarized pump light-waves are generated by OCS modulation to keep the same polarization direction and phase locking between two pumps. This scheme also has excellent advantages such as small size, high-gain, polarization insensitivity, and low-frequency bandwidth requirement for RF signal and optical components, and high wavelength stability. The results of above two mentioned experiments show that the scheme based on dual-pump FWM in a SOA is one of the most promising all-optical up-conversions for radio-over-fiber systems.

2. OFDM signal generation in our system description

In this section the basic functions of the generation in our system are described. The OFDM baseband signals are calculated with a Matlab program including mapping 2^{15}-1 PRBS into 256 QPSK-encoded subcarriers, among them, 200 subcarriers are used for data and 56 subcarriers are set to zero as guard intervals. The cyclic prefix in time domain is 1/8, which would be 32 samples every OFDM frame. Subsequently converting the OFDM symbols into the time domain by using IFFT and then adding 32 pilots signal in the notch. The guard interval length is 1/4 OFDM period. 10 training sequences are applied for each 150 OFDM-symbol frame in order to enable phase noise compensation. At the output the AWG low-pass filters (LPF) with 5GHz bandwidth are used to remove the high-spectral components. The digital waveforms are then downloaded to a Tektronix AWG 610 arbitrary waveform generator (AWG) to generate a 2.5Gb/s electrical OFDM signal waveform.

3. AOWC based on FWM in SOA for OFDM signal

AOWC has been regarded as one of the key techniques for wavelength-division-multiplexing (WDM) optical networks and photonic switch blocks and it can enhance the flexibility of WDM network management and interconnection [30-35]. Nowadays, there are some main techniques for wavelength conversion, which include XGM [33], XPM [34] and FWM [35-38].FWM is considered to be the most promising scheme because it is fully transparent to the signal bit rate and modulation format.

OFDM is as one of the key techniques for 4G (the Fourth Generation Mobile Communication System), immune to fiber dispersion and polarization mode dispersion in optical fiber communication [39-42]. AOWC based on FWM in SOA for regular signal, such as OOK signals, has already been investigated but not for OFDM signals.

We have theoretically analyzed and experimentally demonstrated three schemes for pumping, including single-pump, orthogonal-dual-pump and parallel-dual-pump based on the FWM effect for OFDM signal in SOA for wavelength conversion. Analysis result shows that: (1) the new converted wavelength signal carry the original signal, (2)single-pump scheme is sensitive to polarization, while orthogonal-dual-pump and parallel-dual-pump schemes are insensitive to polarization, (3)parallel-dual-pump scheme has the highest wavelength conversion efficiency, (4)Conversion efficiency of the converted signals are proportional to the amplitudes of the input signal and the pumps. In the single pump scheme, the conversion efficiency depends on the polarization angle between the pump and signal lightwave. In these dual-pump schemes, the conversion efficiency also depends on the frequency spacing between the pumps or between the signal and pump lightwave.

3.1 Theory and result

Figure 1 shows the configuration of all-optical wavelength conversion systems based on FWM for OFDM signal in a SOA. In the system, OFDM signal can be modulated on to a light wave generated from a distributed feedback laser diode(DFB-LD1) by an external intensity modulator (IM),two pumps are generated from DFB-LD2 and DFB-LD3, the modulated signal light wave and pump light waves are coupled and then amplified by EDFA before they are injected into the SOA for FWM process. After wavelength conversion and optical filtering by a circulator and a FBG, the new converted signal carried original signal can be obtained.

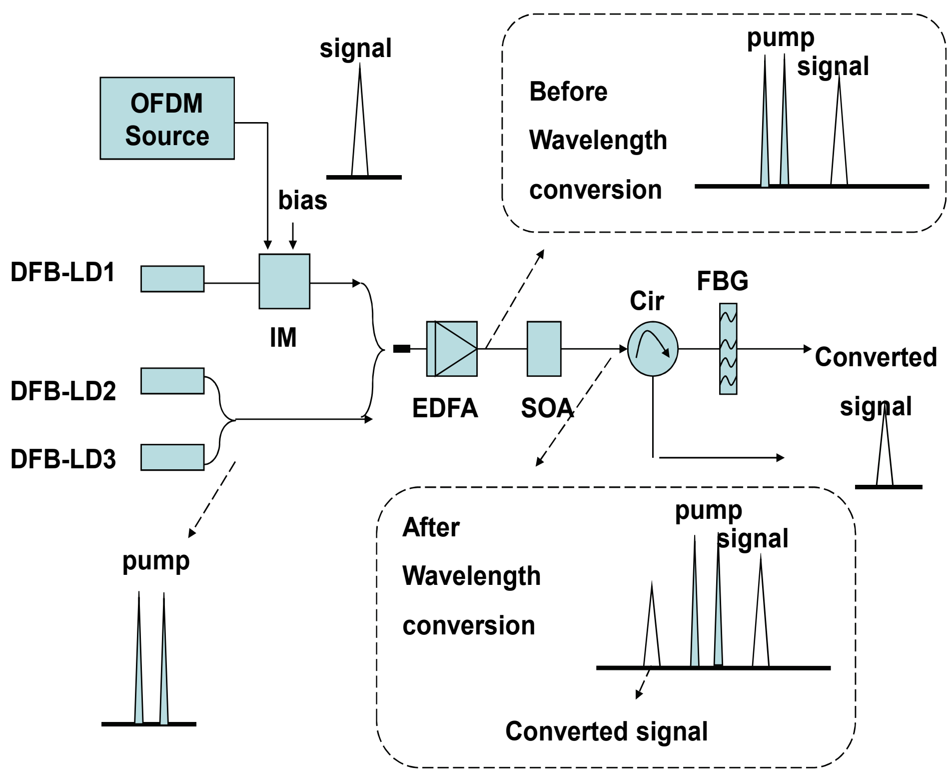


Fig. 1. Configuration of all-optical wavelength conversion systems based on FWM in a SOA. DFB-LD: Distributed feedback-laser diode. FBG: Fiber bragg grating. IM: Intensity modulator. SOA: Semicondoctor optical amplifier. Cir: Circulator.

Fig. 2 shows the principle of all-optical wavelength conversion systems based on FWM effect in an SOA. We build a coordinate system: for simplicity, the signal is assumed to be aligned with the X axis(horizontal orientation),Y axis(vertical orientation), pump1 is at some angle θ with respect to the X axis, and pump2 is at some angle ϕ with respect to X axis. After being amplified by an SOA, the optical field of pump light waves can be expressed as $E_i(\omega_i, \bar{\mathrm{r}}, \mathrm{t}) = E_\mathrm{i}(\omega_\mathrm{i}, \bar{\mathrm{r}})\exp \mathrm{j}\left(\mathrm{k_i z}\text{-}\omega_i \mathrm{t}\text{+}\phi_i\right)$ (i=1,2). Here, $\mathrm{k_i}$, ω_i = ϕ_i represent optical wave vector, angle frequency and phase, respectively. i=1,2 represent pump1 and pump2. The optical field of modulated signal light wave can be expressed as follows:

$$E_3(\omega_3, \vec{r}, t) = A_3 E_3(\omega_3, \vec{r}) \exp j(k_3 z - \omega_3 t + \phi_3) \quad (1)$$

Here, A_3 represents the amplitude of the signal light wave. According to the principle of the four wave mixing effect, it can be envisaged as pairs of light waves to generate a beat, which modulate the input fields to generate upper or lower sidebands.

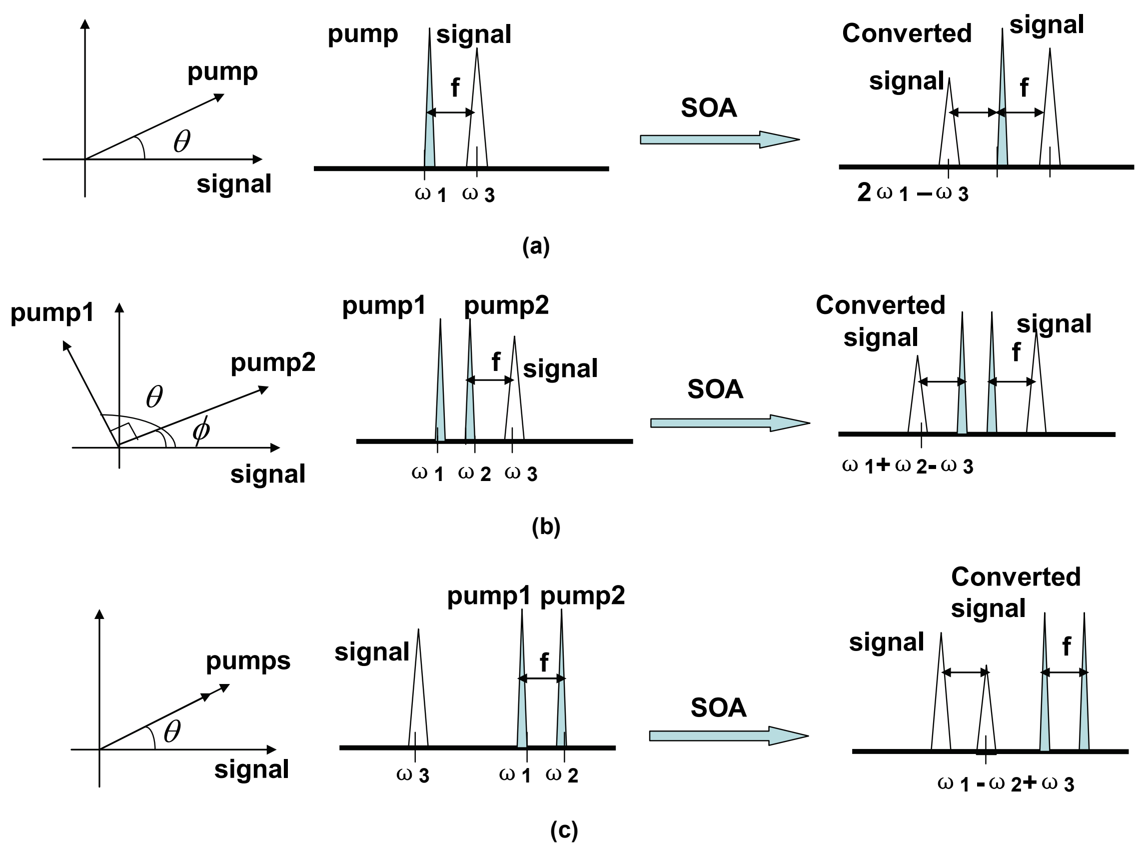


Fig. 2. Principle of all-optical wavelength conversion based on FWM effect. (a)single pump. (b)orthogonal pump. (c) parallel pump

3.1.1 Principle of single-pump configuration for wavelength conversion

In the single-pump configuration, a signal light wave and a pump light wave generate a beat $|\omega_1 - \omega_3|$, and its amplitude can be expressed as:

$$\alpha = r(\omega_1 - \omega_3)[(\vec{A}_1\vec{A}_3^*)\exp j(\omega_1 - \omega_3)t + (\vec{A}_1^*\vec{A}_3)\exp j(\omega_3 - \omega_1)t] \tag{2}$$

The beat $|\omega_1 - \omega_3|$ modulates ω_1 to produce upper and lower sidebands around ω_1 with frequency span of $|\omega_1 - \omega_3|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{\mathrm{E}}_s &= \alpha\vec{E}_1(\omega_1)\\ &= r(\omega_1 - \omega_3)[(\vec{A}_1\vec{A}_3^*)\exp j(\omega_1 - \omega_3)t + (\vec{A}_1^*\vec{A}_3)\exp j(\omega_3 - \omega_1)t]\vec{E}_1(\omega_1)\\ &= r(\omega_1 - \omega_3)A_1A_3\cos\theta\vec{A}_1\left\{e^{j(2\omega_1-\omega_3)t+(2\phi_1-\phi_3)} + e^{j(\omega_3 t+\phi_3)}\right\}\end{aligned} \tag{3}$$

The beat $|\omega_1 - \omega_3|$ modulates ω_3 to produce upper and lower sidebands around ω_3 with a frequency span of $|\omega_1 - \omega_3|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{\mathrm{E}}_s &= \alpha\vec{E}_3(\omega_3)\\ &= r(\omega_1 - \omega_3)[(\vec{A}_1\vec{A}_3^*)\exp j(\omega_1 - \omega_3)t + (\vec{A}_1^*\vec{A}_3)\exp j(\omega_3 - \omega_1)t]\vec{E}_3(\omega_3)\\ &= r(\omega_1 - \omega_3)A_1A_3\cos\theta\vec{A}_3\left\{e^{j(\omega_1 t+\phi_1)} + e^{j(2\omega_3-\omega_1)t+(2\phi_3-\phi_1)}\right\}\end{aligned} \tag{4}$$

What we are interested in is the optical frequency $2\omega_1 - \omega_3$, which is contributed by $|\omega_1 - \omega_3|$ modulating ω_1 and ω_3 .Then, the optical field of new generated frequency wavelength can be expressed as:

$$\vec{\mathrm{E}}_{2\omega_1-\omega_3} = (E_1.E_3^*)E_1 = A_1A_3r(\omega_1-\omega_3)\cos\theta\vec{A}_1e^{j[(2\omega_1-\omega_3)t+(2\varphi_1-\varphi_3)]} \qquad (5)$$

Here, A_1 and A_3 represent the amplitudes of pump and newly converted signal light wave after four wave mixing effect, respectively. $r(\omega_1 - \omega_3)$ is the conversion efficiency coefficient which is proportional to the frequency difference. On the basis of Eq. (5), we can derive the expression of optical power of the new signal as follows:

$$P_{2\omega_1-\omega_3} = A_1^2A_3^2r^2(\omega_1-\omega_3)\cos(\theta) \qquad (6)$$

From Eq. (6) we can see that the output optical power is dependent on the frequency difference and the polarization angle between the pump and signal lightwave. The greater the frequency difference, the lower the conversion efficiency. When the polarization of the pump and the signal light are parallel, the output optical power takes maximum value. When the polarization of the pump and the signal light are orthogonal, the output optical power takes minimum value. From the above analysis, it appears that single-pump configuration is a polarization sensitive system.

3.1.2 Principle of orthogonal-pump configuration for wavelength conversion

In the orthogonal-pump configuration, three light waves with the frequencies of ω_1 , ω_2 and ω_3 generate three beats $|\omega_1-\omega_2|$, $|\omega_1-\omega_3|$ and $|\omega_2-\omega_3|$, each beat will modulate each input lightwave and generate two sidebands

The amplitude of beat $|\omega_1-\omega_3|$ can be expressed as:

$$\alpha = r(\omega_1-\omega_3)[(\vec{A}_1\vec{A}_3^*)\exp j(\omega_1-\omega_3)t + (\vec{A}_1^*\vec{A}_3)\exp j(\omega_3-\omega_1)t] \qquad (7)$$

The beat $|\omega_1-\omega_3|$ modulates ω_2 to produce upper and lower sidebands around ω_2 with frequency span of $|\omega_1-\omega_3|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{\mathrm{E}}_s &= \alpha\vec{E}_3(\omega_3)\\ &= r(\omega_1-\omega_3)[(\vec{A}_1\vec{A}_3^*)\exp j(\omega_1-\omega_3)t + (\vec{A}_1^*\vec{A}_3)\exp j(\omega_3-\omega_1)t]\vec{E}_2(\omega_2)\\ &= r(\omega_1-\omega_3)A_1A_3\cos\theta\vec{A}_2\left\{e^{j[(\omega_2+\omega_1-\omega_3)t+(\phi_2+\phi_1-\phi_3)]} + e^{j[(\omega_2+\omega_3-\omega_1)t+(\phi_2+\phi_3-\phi_1)]}\right\}\end{aligned} \qquad (8)$$

The amplitude of the beat $|\omega_2-\omega_3|$ can be expressed as:

$$\alpha = r(\omega_2-\omega_3)[(\vec{A}_2\vec{A}_3^*)\exp j(\omega_2-\omega_3)t + (\vec{A}_2^*\vec{A}_3)\exp j(\omega_3-\omega_2)t] \qquad (9)$$

The beat $|\omega_2-\omega_3|$ modulates ω_1 to produce upper and lower sidebands around ω_1 with the frequency span of $|\omega_2-\omega_3|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{E}_s &= \alpha \vec{E}_1(\omega_1)\\ &= r(\omega_2-\omega_3)[(\vec{A}_2\vec{A}_3^*)\exp j(\omega_2-\omega_3)t + (\vec{A}_2^*\vec{A}_3)\exp j(\omega_3-\omega_2)t]\vec{E}_1(\omega_1)\\ &= r(\omega_2-\omega_3)A_2A_3\cos(\phi)\vec{A}_1\left\{e^{j[(\omega_1+\omega_2-\omega_3)t+(\phi_1+\phi_2-\phi_3)]}+e^{j[(\omega_1+\omega_3-\omega_2)t+(\phi_1+\phi_3-\phi_2)]}\right\}\end{aligned} \tag{10}$$

What we are interested in is optical frequency $\omega_1+\omega_2-\omega_3$, which is contributed by $|\omega_1-\omega_3|$ modulating ω_2 and $|\omega_2-\omega_3|$ modulating ω_1 .Thus, after a SOA the optical field of newly generated frequency wavelength can be expressed as:

$$\begin{aligned}\vec{E}_{\omega_1+\omega_2-\omega_3} &= (E_1.E_3^*)E_2 + (E_2.E_3^*)E_1\\ &= [r(\omega_1-\omega_3)A_1A_3\cos\theta\vec{A}_2 + r(\omega_2-\omega_3)\cos(\phi)A_2A_3\vec{A}_1]e^{j[(\omega_1+\omega_2-\omega_3)t+(\phi_1+\phi_2-\phi_3)]}\end{aligned} \tag{11}$$

When $\theta-\phi=\frac{\pi}{2}$, it means that the signal and pump are orthogonally polarized, namely,

$$\cos\phi = \cos(\frac{\pi}{2}-\theta) = \sin\theta \tag{12}$$

Eq. (11) can be written as following:

$$\begin{aligned}\vec{E}_{\omega_1+\omega_2-\omega_3} &= (E_1.E_3^*)E_2 + (E_2.E_3^*)E_1\\ &= [r(\omega_1-\omega_3)A_1A_3\cos\theta\vec{A}_2 + r(\omega_2-\omega_3)A_2A_3\sin(\theta)\vec{A}_1]e^{j[(\omega_1+\omega_2-\omega_3)t+(\phi_1+\phi_2-\phi_3)]}\end{aligned} \tag{13}$$

Here, A_1, A_2 and A_3 represent the amplitudes of pumps and newly converted signal light wave after four wave mixing effect, $r(\omega_1-\omega_3)$ and $r(\omega_2-\omega_3)$ represent the conversion efficiency coefficient , which is inversely proportional to the frequency difference. From Eq. (13) ，It can be seen that the output power of the optical frequency is:

$$P_{\omega_1+\omega_2-\omega_3} = A^2{}_3[r^2(\omega_1-\omega_3)A_1^2A_2^2\cos^2\theta + r^2(\omega_2-\omega_3)A_2^2A_1^2\sin^2\theta] \tag{14}$$

Because $|\omega_1-\omega_3| \approx |\omega_2-\omega_3|$, we obtain: $r(\omega_1-\omega_3) \approx r(\omega_2-\omega_3)$
Therefore, Eq. (13) can be simplified to

$$P_{\omega_1+\omega_2-\omega_3} = A^2{}_3r^2(\omega_1-\omega_3)A_1{}^2A_2{}^2(\cos^2\theta+\sin^2\theta) = A_1{}^2A_2{}^2A^2{}_3r^2(\omega_1-\omega_3) \tag{15}$$

It can be seen that output signal optical power is independent of θ, that is to say, the orthogonal-dual-pump configuration is a polarization insensitive system, and its optical power relies on $r(\omega_1-\omega_3)$ with the interval of pump and signal light wave frequency increasing, the optical power gradually decrease.

3.1.3 Principle of parallel-dual-pump configuration for wavelength conversion

In the parallel-dual-pump configuration, three light waves with frequency of ω_1, ω_2 and ω_3 generate three beats $|\omega_1-\omega_2|$, $|\omega_1-\omega_3|$ and $|\omega_2-\omega_3|$, each beat will modulate each input lightwave and generate two sidebands.

The amplitude of beat $|\omega_1 - \omega_2|$ can be expressed as:

$$\alpha = r(\omega_1 - \omega_2)[(\vec{A}_1\vec{A}_2^*)\exp j(\omega_1 - \omega_2)t + (\vec{A}_1^*\vec{A}_2)\exp j(\omega_2 - \omega_1)t] \tag{16}$$

The beat $|\omega_1 - \omega_2|$ modulates ω_3 to produce upper and lower sidebands around ω_3 with the frequency span of $|\omega_1 - \omega_2|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{E}_s &= \alpha\vec{E}_3(\omega_3)\\ &= r(\omega_1 - \omega_2)[(\vec{A}_1\vec{A}_2^*)\exp j(\omega_1 - \omega_2)t + (\vec{A}_1^*\vec{A}_2)\exp j(\omega_2 - \omega_1)t]\vec{E}_3(\omega_3)\\ &= r(\omega_1 - \omega_2)A_1A_2\cos\theta\vec{A}_3\left\{e^{j[(\omega_3+\omega_1-\omega_2)t+(\phi_3+\phi_1-\phi_2)]} + e^{j[(\omega_3+\omega_2-\omega_1)t+(\phi_3+\phi_2-\phi_1)]}\right\}\end{aligned} \tag{17}$$

The amplitude of beat $|\omega_3 - \omega_2|$ can be expressed as:

$$\alpha = r(\omega_3 - \omega_2)[(\vec{A}_3\vec{A}_2^*)\exp j(\omega_3 - \omega_2)t + (\vec{A}_3^*\vec{A}_2)\exp j(\omega_2 - \omega_3)t] \tag{18}$$

The beat $|\omega_3 - \omega_2|$ modulates ω_1 to produce upper and lower sidebands around ω_1 with the frequency span of $|\omega_3 - \omega_2|$ and the optical field can be expressed as:

$$\begin{aligned}\vec{E}_s &= \alpha\vec{E}_1(\omega_1)\\ &= r(\omega_3 - \omega_2)[(\vec{A}_3\vec{A}_2^*)\exp j(\omega_3 - \omega_2)t + (\vec{A}_3^*\vec{A}_2)\exp j(\omega_2 - \omega_3)t]\vec{E}_1(\omega_1)\\ &= r(\omega_3 - \omega_2)A_3A_2\cos\theta\vec{A}_1\left\{e^{j[(\omega_1-\omega_2+\omega_3)t+(\phi_1-\phi_2+\phi_3)]} + e^{j[(\omega_1+\omega_2-\omega_3)t+(\phi_1+\phi_2-\phi_3)]}\right\}\end{aligned} \tag{19}$$

What we are interested in is the optical frequency $\omega_1 - \omega_2 + \omega_3$, which is contributed by the beat $|\omega_1 - \omega_2|$ modulateing ω_3 and beat $|\omega_3 - \omega_2|$ modulateing ω_1

$$\begin{aligned}\vec{E}_{\omega_1-\omega_2+\omega_3} &= (E_1.E_2^*)E_3 + (E_3.E_2^*)E_1\\ &= [r(\omega_1 - \omega_2)A_1A_2\cos(\theta-\phi)\vec{A}_3 + r(\omega_3 - \omega_2)A_3A_2\cos(\phi)\vec{A}_1]e^{j[(\omega_1-\omega_2+\omega_3)t+(\varphi_1-\varphi_2+\varphi_3)]}\end{aligned} \tag{20}$$

Here, A_1, A_2 and A_3 represent the amplitudes of pumps and new converted signal light wave after the four wave mixing effect, $r(\omega_1 - \omega_2)$ and $r(\omega_3 - \omega_2)$ represent conversion efficiency coefficient , which is inversely proportional to the frequency difference.
When $\theta = \phi$, it means that signal and pump are parallel polarized and there is $r(\omega_1 - \omega_2) >> r(\omega_3 - \omega_2)$ because $(\omega_1 - \omega_2)$ is much smaller than $(\omega_3 - \omega_2)$. Therefore, Eq. (20) depends largely on the first term and the second term can be basically ignored. Therefore, the signal polarization has little effect one the output optical power and Eq. (19) reduces to

$$\vec{E}_{\omega_1-\omega_2+\omega_3} = [A_1A_2r(\omega_1 - \omega_2)\vec{A}_3 + A_3A_2r(\omega_3 - \omega_2)\vec{A}_1\cos(\varphi)]e^{j[(\omega_1-\omega_2+\omega_3)t+(\phi_1-\phi_2+\phi_3)\_]} \tag{21}$$

From Eq. (21), It can be seen that the power of the optical frequency is

$$P_{\omega_1-\omega_2+\omega_3} = A_1^2A_2^2A_3^2[r^2(\omega_1 - \omega_2) + r^2(\omega_3 - \omega_2)\cos^2(\phi)] \tag{22}$$

We can see that if the signal light polarization direction is parallel to the pump light polarization ($\phi = 0$), the output power takes a the maximum; whereas, if the signal light polarization direction is orthogonal to that of the pump ($\varphi = \frac{\pi}{2}$), the output power takes a minimum. Therefore, the converted signal power depends on the frequency interval between pumps, signal and pump and the polarization angle between them. However, we can conclude that parallel-dual-pump configuration is polarization insensitive system.

Through the above analysis above, output optical power of the structures of single-pump, orthogonal-dual-pump and parallel double-pump is:

$$\begin{aligned} P_{2\omega_1-\omega_3} &= A_1{}^2 A_3{}^2 r^2(\omega_1-\omega_3)\cos^2(\theta) \\ P_{\omega_1+\omega_2-\omega_3} &= A_1{}^2 A_2{}^2 A^2{}_3 r^2(\omega_1-\omega_3) \\ P_{\omega_1-\omega_2+\omega_3} &= A_1^2 A_2^2 A_3^2[r^2(\omega_1-\omega_2)+r^2(\omega_3-\omega_2)\cos^2(\phi)] \end{aligned} \quad (23)$$

At first, it seems from the above equations that the new wavelength converted signal carries the original signal.

Secondly, because the conversion efficiency coefficient is inversely proportional to the frequency interval, such a relationship $r(\omega_1-\omega_2) >> r(\omega_3-\omega_2)$ that the parallel pump has the highest wavelength conversion efficiency.

Finally, OFDM as one of the key techniques for 4G, is immune to fiber dispersion and polarization mode dispersion in optical fiber communication. We investigated AOWC based on FWM in a SOA for OFDM signal, which is of great significance. If we introduce OFDM signal into a AOWC, A_3 represents the amplitudes of OFDM signal light wave, it is a time-related functions, we can see from the above formula that the new converted wavelength signal carry the original OFDM signal. Therefore, the performance for OFDM signal in AOWC based on FWM in a SOA is the same as that of OOK signal.

3.2 Experimental setup

Fig. 3 shows the experimental configuration setup and results for an all-optical wavelength conversion based on the single pump FWM effect in a SOA. Two continuous lightwaves generated by the DFB-LD1 and DFB-LD2 at 1544.25nm and 1544.72nm, are used for the pump light and signal light. AWG produces 2.5Gb/s based on the orthogonal phase-shift keyed modulation OFDM signal and its electrical spectrum is shown in Fig. 3 (a). The CW light generated by DFB-LD1 at 1544.72nm signal light is modulated via a single-arm LN-MOD biased at 2.32V.The half-wave voltage (vπ) of the LN-MOD is 7.8V, its 3dB bandwidth is greater than 8GHZ, and its extinction ratio is greater than 25dB.The 2.5 Gbit/s optical signals and the pump signal are combined by a optical coupler (OC) before an erbium-doped fiber amplifiers (EDFA) which is used to boost the power of the two signals. The optical spectra before and after SOA are shown in Fig. 3 (b) and (c), respectively. The optical power of the signal light, pump lights are 5.38dBm, 8.8dBm and 8.0dBm, respectively. As shown in Fig3(c), wavelength of the converted signal is 1543.78nm, optical signa-to-noise power ratio(OSNR) is 25dBm.The wavelength conversion efficiency is -15dB.A FBG with a 3dB bandwidth of 0.15nm and a TOF with a 0.5 nm bandwidth is used to filter out the converted signal. The converted OFDM signal is send to 10Gb/s optical receiver. The OFDM signal detected from optical receiver is sent to a real-time oscilloscope for data collection.

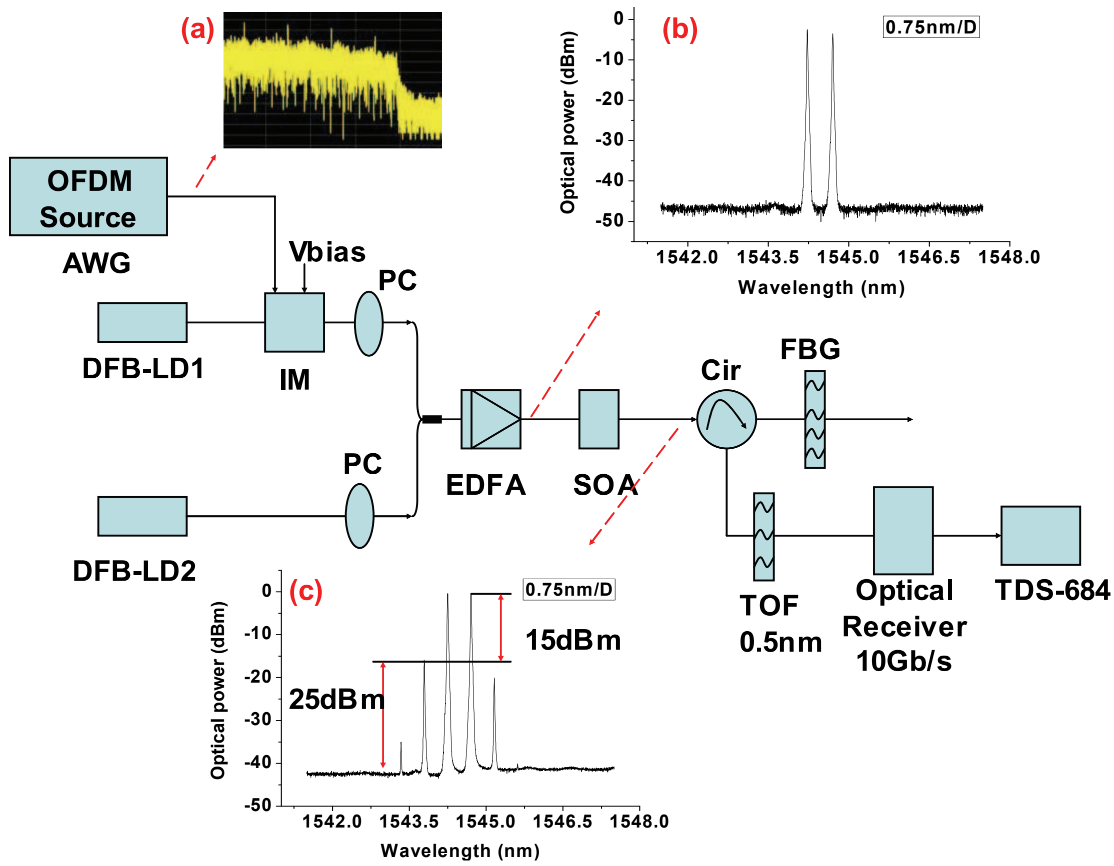


Fig. 3. Configuration of experimental setup and results for all-optical wavelength conversion based on single pump FWM effect in SOA.(a) Electrical spectra of the OFDM signal; (b)optical spectral of the combined signals before SOA; (c)optical spectra of signal after SOA. DFB-LD:distributed feedback laser diode; FBG:Fiber bragg grating, IM:Intensity modulator, SOA:Semiconductor optical amplifier ,Cir:Circulator; TOF: Tunable optical filter

Fig. 4 shows the experimental configuration setup and results for the all-optical wavelength conversion based on the single pump FWM effect in a SOA. Two continuous lightwaves generated by the DFB-LD2 and DFB-LD3 at 1544.15nm and 1544.65nm, are used for the pump lights. AWG produces 2.5Gb/s based on the orthogonal phase-shift keyed modulation OFDM signal, and its electrical spectrum is shown in Fig4 (a). The CW light generated by DFB-LD1 at 1545.05nm is modulated via a single-arm LN-MOD biased at 1.62V.The half-wave voltage ($v\pi$) of the LN-MOD is 7.8V, its 3dB bandwidth is greater than 8GHz and its extinction ratio is greater than 25dB.The 2.5 Gbit/s optical signals and the pump signals are combined by a optical coupler (OC) before EDFA to boost the power of the two signals. The optical spectra before and after SOA are shown in Fig.4 (b) and (c), respectively. The optical power of the signal light and pump lights are 5.7dBm, 11.6dBm and 11.6dBm, respectively. As shown in Fig4(c), the wavelength of the converted signal is 1543.76nm, optical signal-to-noise power ratio(OSNR) is 25dBm.The wavelength conversion efficiency is -15dB.A FBG with a bandwidth of 0.15nm and a TOF with a 0.5 nm bandwidth is used to filter out the converted signal. The converted OFDM signal is sent to the 10Gb/s optical receiver. The OFDM signal detected from optical receiver is then sent to the real-time oscilloscope for data collection.

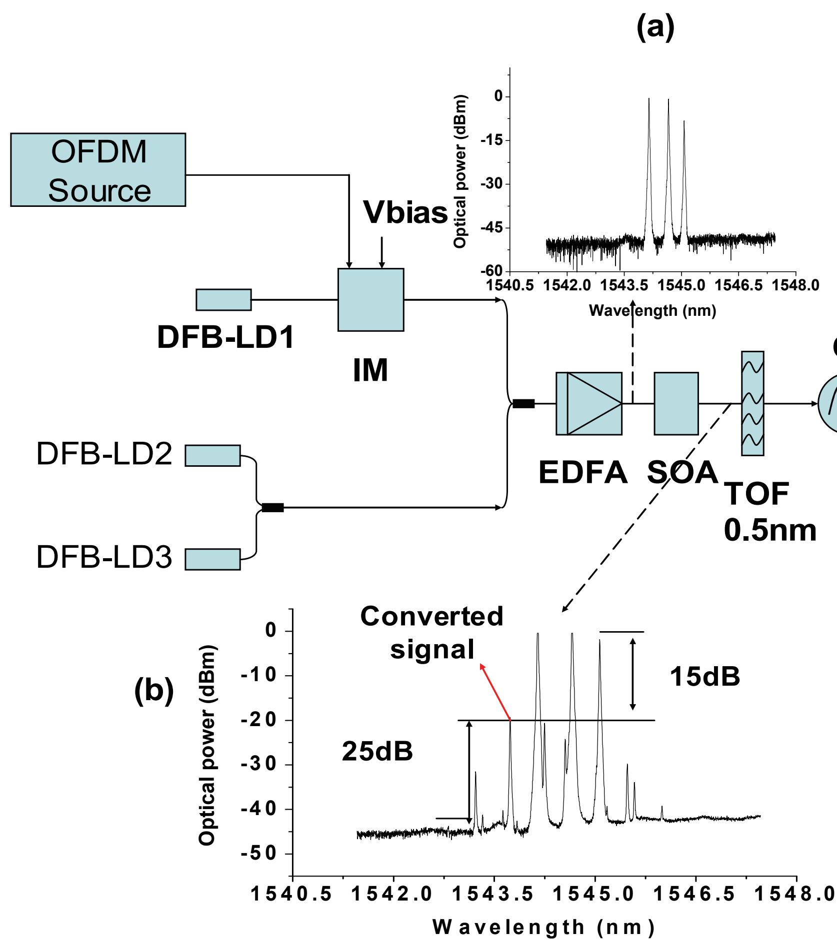


Fig. 4. Configuration of experimental setup and results for all-optical wavelength conversion based on orthogonal-dual-pump FWM effect in SOA.(a) Electrical spectra of the OFDM signal;(b)optical spectral of the combined signals before SOA;(c)optical spectra of signal after SOA. DFB-LD:distributed feedback laser diode; FBG:Fiber bragg grating, IM:Intensity modulator, SOA:Semicondoctor optical amplifier ,Cir:Circulator; TOF: Tunable optical filter. OSC: oscillator.

Fig. 5 shows the experimental configuration setup and results for the all-optical wavelength conversion based on the single pump FWM effect in a SOA. Two continuous lightwaves generated by the DFB-LD2 and DFB-LD3 are used for the pump lights. AWG produces 2.5Gb/s based on the orthogonal phase-shift keyed modulation OFDM signal, its electrical spectrum is shown in Fig.5 as inset (i). The CW light generated by DFB-LD1 at 1544.72nm signal light is modulated via a single-arm LN-MOD biased at 1.62V.The half-wave voltage ($v\pi$) of the LN-MOD is 7.8V, its 3dB bandwidth is greater than 8GHz, and its extinction ratio is greater than 25dB.The 2.5 Gbit/s optical signals and the pump signals are combined by an optical coupler (OC) before an EDFA to boost the power of the two signals. The optical spectra before and after a SOA are shown in Fig.5 (a) and (b), respectively. The optical power of the signal lightwave and pump lightwaves are 2.0dBm, 6.5dBm and 8.9dBm, respectively. As shown in Fig5(b), wavelength of the converted signal is 1543.78nm, optical signal-to-noise power ratio(OSNR) is 23dBm.The wavelength conversion efficiency is -17dB.A FBG with a 3dB bandwidth of 0.15nm and a TOF with 0.5 nm bandwidth is used to filter out the converted signal. The converted OFDM signal is sent to the 10Gb/s optical receiver. The OFDM signal detected from optical receiver is sent to real-time oscilloscope for data collection. The received electrical spectrum is shown in Fig.5 as inset (ii).

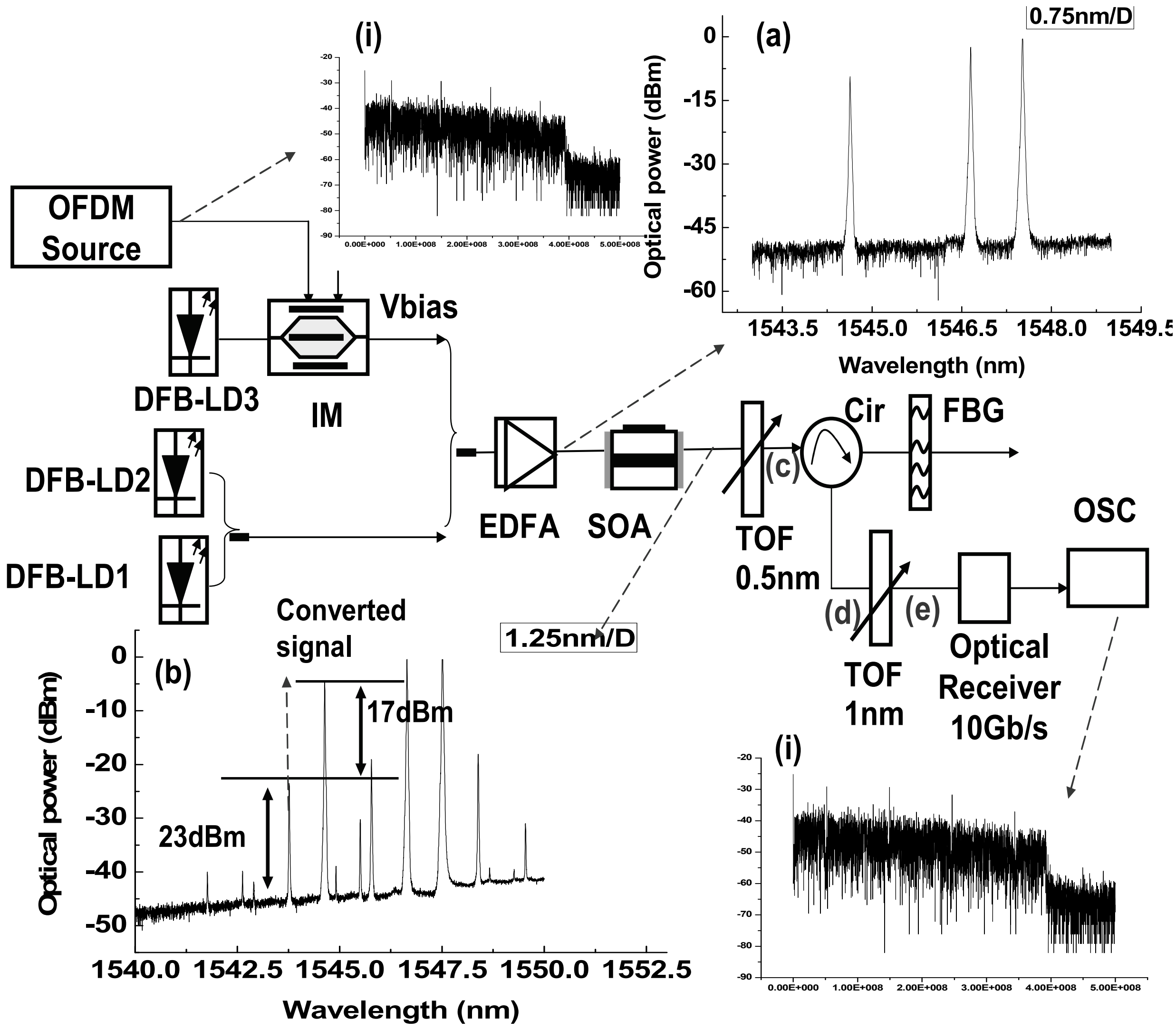


Fig. 5. Configuration of experimental setup and results for all-optical wavelength conversion based on parallel-dual-pump FWM effect in SOA.(i) Electrical spectra of the original OFDM signal; (ii) Electrical spectra of the converted OFDM signal; (a)optical spectral of the combined signals before SOA;(b)optical spectra of signal after SOA. DFB-LD:distributed feedback laser diode; FBG:Fiber bragg grating, IM:Intensity modulator ,SOA:Semicondoctor optical amplifier ,Cir:Circulator; TOF: Tunable optical filter. OSC: oscillator.

3.3 Experimental results

3.3.1 The comparison of Conversion efficiency

In the experiment, we measured the original signal and the pump optical power, the optical signal-to-noise ratio and the conversion efficiency of the three configurations as following table 1 show:

	Single-pump	Orthogonal-pump	parallel-pump
Original signal	5.38dBm	5.7dBm	2.0dBm
Pump1	8.8dBm	11.6dBm	6.5dBm
Pump2	8.0dBm	11.6dBm	8.9dBm
OSNR	25dB	25dB	23dB
Conversion efficiency	-15dB	-15dB	-17dB

Table 1. Comparison of three configurations

From the table we can see that the when three configurations in terms of optical signal-to-noise ratio and conversion efficiency are similar, the original signal light and pumped optical power of parallel-double-pump configuration are minimal, that means this scheme has the highest conversion efficiency. So, the experimental results are agreed well with the theoretical analysis.

3.3.2 The comparison of power penalty

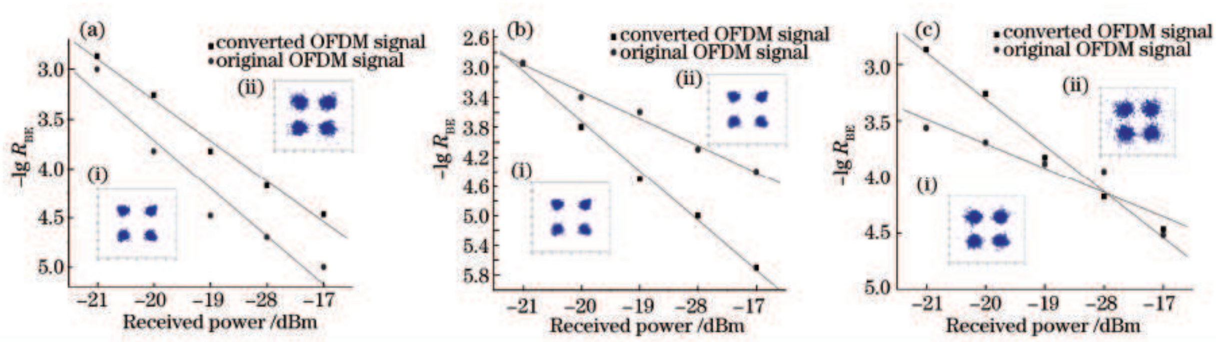


Fig. 6. The bit error rate (BER) curves and received constellations of three configuration

From the Fig. 6 we can see that the power penalty of parallel-dual-pump configuration is minimal compared to the other two configurations. After wavelength conversion, the converted signal is still OFDM signal, and the difference of received constellations between original and converted signal of parallel-dual-pump configuration is minimal, that is to say, this configuration has the smallest bit error rate (BER)

In conclusion, FWM based on SOA is considered to be the most promising scheme because it is fully transparent to the signal bit rate and modulation format, combined with OFDM signals, it can enhance the performance of optical networks, and is of significance for realizing all optical networks. On the other side, orthogonal-dual-pump and parallel-dual-pump schemes are polarization insensitive schemes. We can employ these schemes for all-optical up-conversion for ROF system.

4. The application of SOA in ROF system

The ROF converge two most important conventional communication technologies: radio frequency (RF) for wireless and optical fiber for wired transmission. It can afford huge bandwidth and communication flexibility, besides it can transmit wireless or wired signal to long distance region. So it becomes a very attractive technology in access network [43-48]. However, we still have to solve many problems in ROF system, such as simplify the base station and generation of high-frequency millimeter (mm)-wave [44, 47-48], In order to generate high-frequency mm-wave, we have tried many types of schemes [48-53]. In Ref. [50], we proposed a novel scheme to generate frequency-quadruple optical mm-wave radio-over-fiber system based on suppression odd-sideband by using one external modulator and cascaded Fiber Bragg Grating (FBG) filter.

Apart from this, there are many other suggestions to generate high-repetitive frequency millimeter (mm)-wave. Some researchers suggest we can use the nonlinear effects of some medium to generate mm-wave, such as XPM, SPM and FMW.FWM has the unique advantage of being transparent to the modulation format and the bit rate, which is of critical importance when handling analog or digital signals with speed of hundreds gigabit per second (difficult with XGM and XPM) [4, 13, 36, 54]. The medium which researchers are most interested in are HNLF and SOA [6].

In Ref. [55], H. Song etc. use the SOA-MZI (semiconductor optical amplifier Mach-Zehnder interferometer) to realize frequency up conversion to mm -wave, this just use the XPM effect in the SOA to generate the mm-wave. Many researchers preferred to use the FWM to generate mm-wave [6, 56-60].The reason is we can get cost-effective mm-wave by using FWM effect compared with other two nonlinear effects of high nonlinear medium. In 2006, J. Yao etc. proposed millimeter-wave frequency tripling based on FWM in a SOA [56]. In this article two signals are not phase and polarization locked , in order to keeping the phase of the two signal locked they used the optical phase-locked loop (OPLL), but they can not ensure the polarization of two signal and this directly leads to the low conversion efficiency . To improve the conversion efficiency, A. Wiberg used the OCS intensity modulation to generate two phase-locked wavelengths, and then he used these two wavelengths as two pumps to generate two new sidebands through the FWM effect in HNLF [61]. Through this scheme, a frequency six times of the electrical drive signal is obtained. It also improved the conversion efficiency. In this scheme A. Wiberg used HNLF instead of SOA, as we know the FWM in SOA has the following advantages against in HNLF:

a. In order to generate the two new sidebands with high power, the power of two pumps must be very high and the HNLF length should be long, which makes the system bulky and costly;
b. When pump power is very high, other nonlinear except FWM such as simulated Brillouin scattering (SBS), SPM and XPM may appear which will degrade the conversion efficiency.

To avoid difficult caused by using FWM effect of HNLF, J. Yao etc. suggested to use SOA instead of HNLF, and the pump are also two phase-locked generated by OCS intensity modulation [57].Then S. Xie etc. also proposal some scheme based on FWM effect of SOA to generate mm-wave [58-60].In Ref. [58], they use two cascaded optical modulators and FWM effect in SOA to generate a 12 times microwave source frequency with high spectral purity. First they generated frequency-quadruple optical mm-wave, then the optical lightwave is injected into SOA to get a 12 times microwave source frequency mm-wave. Since only one integrated MZM can also generate a frequency-quadruple optical mm-wave [62], So P.T. Shih etc. used only one MZM and SOA to get a 12 times microwave source frequency mm-wave [63]. What we have discussed above is just FWM effect of SOA when only two signals injected into SOA. Many researchers also investigated what will happen if they inject three signals (two of them are pump signals, another is probe signal) into SOA. They found FWM can also occur when certain conditions are met [64].

H. J. Kim accomplished all-optical up-conversion for ROF system through FWM in SOA because of its positive conversion efficiency and wide LO frequency bandwidth [64]. However, only double frequency mm-wave is generated and polarization sensitivity of this FWM system is not discussed in [64].Recently, polarization insensitive FWM in nonlinear optical fiber based on co-polarized pump scheme has been demonstrated in [6, 35], which is an effective way to increase the system stability. In Ref. [6, 35], two pumps are generated from different laser sources; therefore, the phase is not locked. Moreover, two polarization controllers (PC) are used to keep the two lightwaves to have the same polarization direction. We have investigated whether FWM is polarization sensitive in SOA based on co-polarized pump scheme, we proved FWM is polarization insensitive with parallel pump [52, 65-66], Configuration of experimental setup and results for all-optical wavelength conversion based on parallel-pump FWM effect in SOA shows in Fig.5.Three DFB generate pump and probe signals, two of them are used as pumps, another is probe. We must keep the pumps phase-locked and parallel. We try to change the polarization direction of the probe, the converted lightwaves are constant. We can see two converted signals in both sides of the probe signal, then we get any two of three lightwaves, we generate mm-wave after the optical to electrical conversion. And then we find the similar conclusion with orthogonal pumps [53].

In Ref. [57], we experimentally demonstrate all-optical up-conversion of radio-over-fiber signals based on a dual-pump four wave mixing in a SOA for the first time. The co-polarized pump light-waves are generated by OCS modulation to keep the same polarization direction and phase locked between two pumps. The proposed scheme to realize all-optical up-conversion based on FWM in a SOA is shown in Fig. 7. It is similar to the up-conversion scheme by nonlinear optical fiber [6]. The OCS signal is generated by an

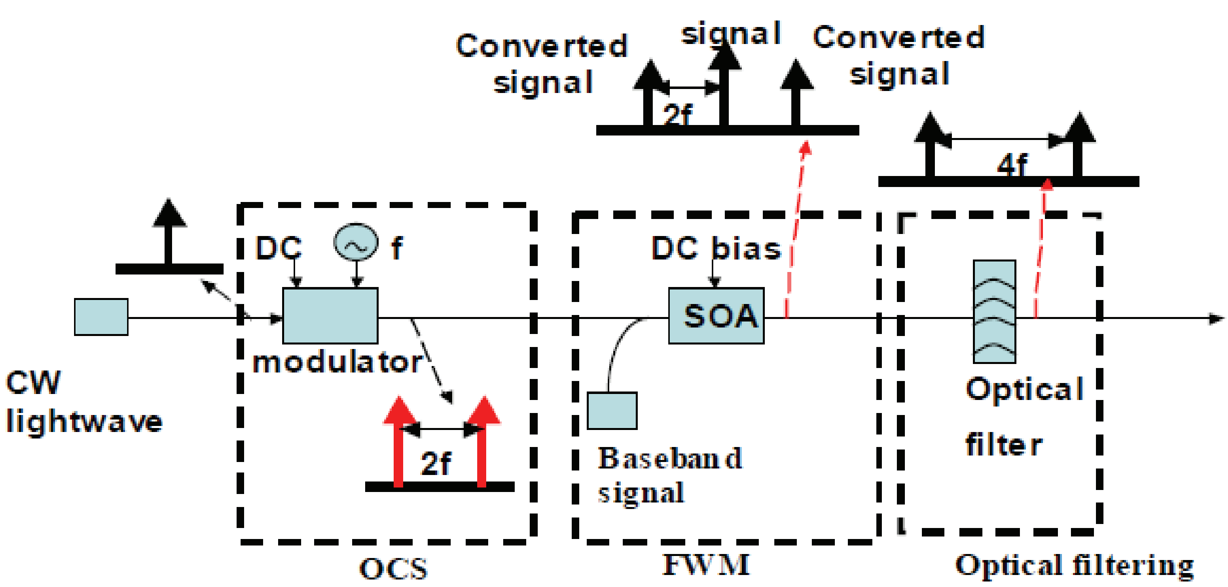


Fig. 7. The principle diagram of polarization-insensitive all-optical up-conversion based on FWM effect in a SOA. The repetitive frequency of the RF signal is f, and the IM's DC is biased at null point.

external intensity modulator (IM) biased at null point. The continuous wave (CW) lightwave generated by a DFB array is modulated via a single-arm IM driven by a RF sinusoidal wave signal with a repetitive frequency of f based on the OCS modulation scheme to generate two subcarriers with wavelength spacing of 2f. The generated two lightwaves, which will be used as pump signals, have the same polarization direction, optical power, and locked phase. The two converted signals with channel spacing of 4f can be obtained after FWM effect in SOA. The two converted signals have the same polarization direction and locked phase as well. When the pumps and original signal are removed by optical filters, the all-optical up-converted signals carried by 4f optical carrier are achieved.

Fig. 8 shows the experimental setup for single channel up conversion. In the central office (CO), the continuous lightwave generated by the DFB-LD0 at 1550nm is modulated by a single-arm LN-MOD biased at $v\pi$ and driven by an 10GHz LO to realize OCS. The repetitive frequency of the LO optical signal is 20GHz, and the carrier suppression ratio is larger than 20 dB. The high sidebands are removed by a 50/100 GHz IL, and the optical spectrum is shown in Fig. 8 as inset (i). The CW generated by DFB-LD1 at 1543.82 nm is modulated via another LN-MOD driven by 2.5-Gb/s pseudorandom binary sequence data with a length of $2^{31}-1$ to generate regular OOK non-return-to-zero (NRZ) optical signals. The 2.5 Gbit/s optical signals and the 20 GHz OCS pump signals are combined by a 3-dB OC before two individual EDFA are used to boost the power of the two signals respectively. The SOA is

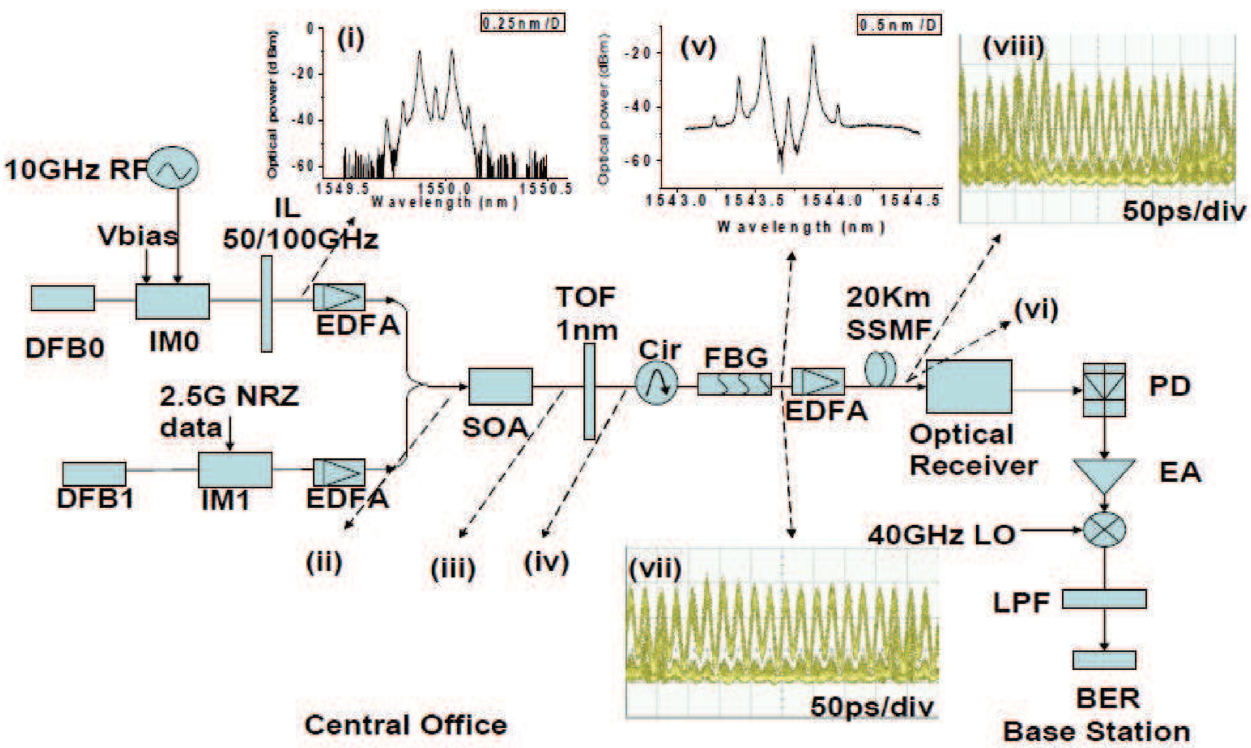


Fig. 8. Experimental setup and results for all-optical up-conversion base on four-wave mixing in SOA, Cir: optical circulator, TOF: tunable optical filter, EA: electrical amplifier. Inset (i): OCS signals after IL; (ii): the combined signals after OC; (iii): combined signals after SOA; (iv): converted DSB signals after 1nm TOF; (v): converted OCS signal after FBG; (vi): converted OCS signal after transmission; (vii): the mm-wavesignals before transmission; (viii): the mm-wave signals after transmission

injected by 200 mA, which gives 25 dB gain and 10 dBm saturation optical power. This SOA has polarization sensitivity smaller than 0.5 dB. The DSB signals with 40-GHz spaces between first order sidebands are created from 2.5-Gbit/s NRZ signals by the FWM effect in the SOA. A TOF with 1nm optical bandwidth is used to remove the pump signals while get the DSB signals. The carrier suppression signals with 40-GHz space are generated by using an optical circulator and a FBG. The FBG has a 3 dB reflection bandwidth of 0.2 nm. The optical spectra after FBG are shown in Fig. 8 as inset (v).

The OCS signals are detected by an optical receiver after transmission over 20-km SMF-28 before they are amplified by an EDFA. The eye diagrams of the 40-GHz optical mm-wave signals before and after 20-km SSMF-28 transmission can be seen in Fig. 8 insets (vii) and (viii), respectively. At the base station (BS), the optical signals are detected by an optical receiver. A TOF with 0.5 nm bandwidth is used to remove the ASE noise. After the optical receiver, the mm-wave signal with the down-link data is detected by an optical–electrical (O/E) converter with a 3-dB bandwidth of 40-GHz and amplified by a narrow-band electrical amplifier (EA), after these we get a frequency-quadruple of LO optical mm-wave. This scheme has excellent advantages such as small size, high-gain, polarization insensitivity, and low-frequency bandwidth requirement for RF signal and optical components, and high wavelength stability. 2.5 Gbit/s baseband signal has been successfully up-converted to 40 GHz carrier in this scheme. The experimental results show that the scheme based on dual-pump FWM in a SOA is one of the most promising all-optical up-conversions for ROF systems.

We then propose and experimentally investigate another polarization insensitive all-optical up-conversion scheme for ROF system based on FWM in a SOA [65]. In this scheme the parallel pump is generated based on optical odd-order sidebands and carrier suppression using an external intensity modulator and a cascaded optical filter. Therefore, the two pumps are always parallel and phase locked, which makes system polarization insensitive. After FWM in a SOA and optical filtering, similar to single sideband (SSB) 40GHz optical millimeter-wave is generated only using 10GHz RF as LO.As we know, SSB modulation is a good option to overcome fiber dispersion [67], we will improve mm-wave performance in this scheme.

Fig. 9 shows the principle of polarization-insensitive all-optical up-conversion for ROF systems based on parallel pump FWM in a SOA. In the central station, an IM and a cascaded optical filter are employed to generate quadruple frequency optical mm-wave, in which the odd-order sidebands and the optical carrier are suppressed. Obviously the generated two second-order sidebands have the parallel polarization direction and phase locked. Then the two pumps are combined with the signal lightwave by using an OC. The two converted new signals can be obtained after FWM process in the SOA. A TOF is used to suppress the pump signal. In this scheme, the optical signal similar to DSB signal is generated, which includes two converted signals and original signal after FWM in SOA. However, when one sideband is removed by an optical filter or optical interleaver(IL), the remaining signal is SSB-like signal, which includes one up-converted sideband and original signals. As we know that SSB signal can realize dispersion free long distance transmission. In the base station, the optical quadruple repetitive frequency mm-wave will be generated when they are detected by O/E converter after transmission.

Fig.10 shows the experimental setup for all-optical up-conversion in [65]. The lightwave generated from the DFB laser at 1543.8nm is modulated by the IM1 driven by a 10GHz sinusoidal wave. The IM1 is DC-biased at the top peak output power when the LO signal is

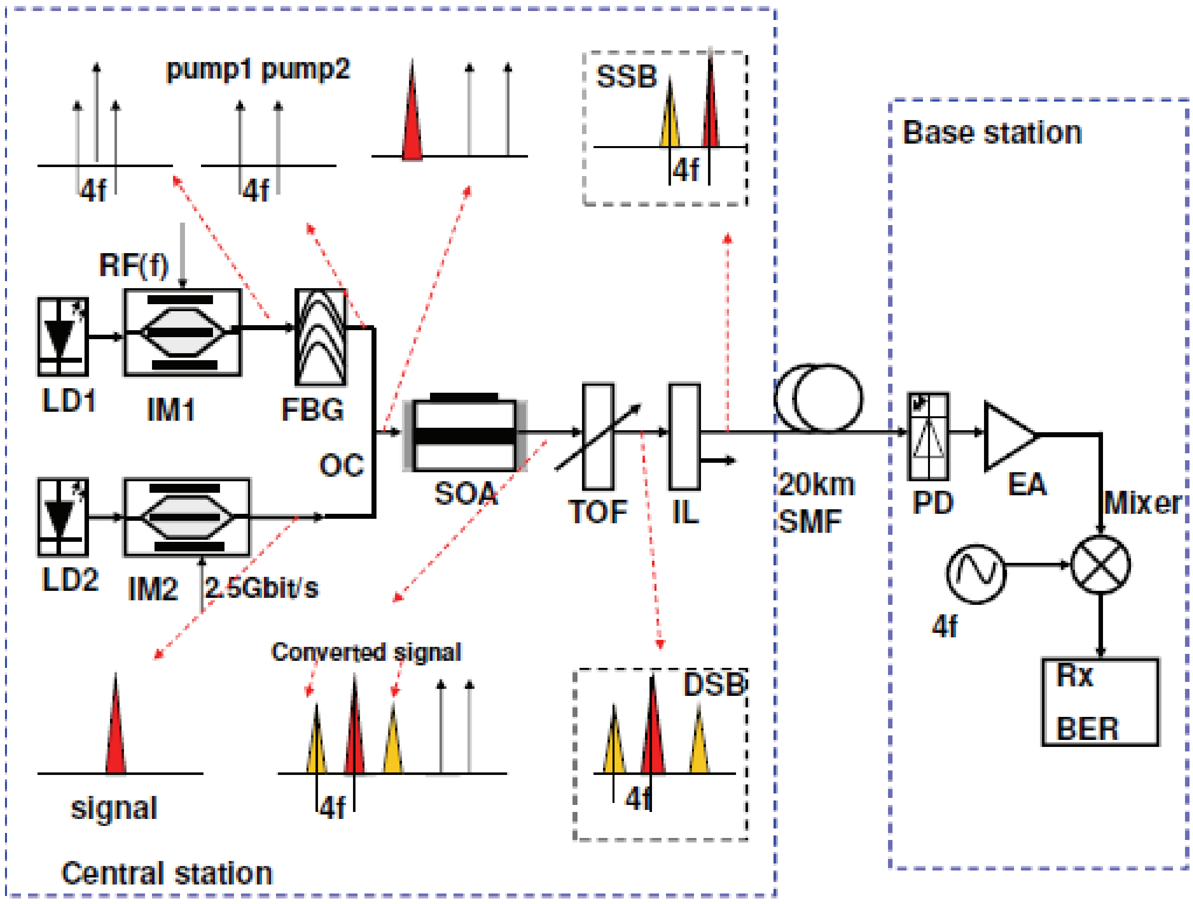


Fig. 9. The principle of polarization-insensitive all-optical up-conversion for ROF system based on parallel pump FWM in a SOA. FBG: fiber Bragg grating. OC: optical coupler. SOA: semiconductor optical amplifier. TOF: tunable optical filter. IL: interleaver. EA: electrical amplifier. IM: intensity modulator. SSB: single sideband. DSB: double sideband. PD: photodiode.BER: bit error ratio. RX: receive

removed. 10GHz RF microwave signal with a peak-to-peak voltage of 12V. The half-wave voltage of the IM is 6V; by this way, the odd-order modes are suppressed. The optical spectrum after IM1 is shown in Fig. 10 as inset (i). We can see that the first-order sidebands are suppressed and the frequency spacing between the second-order modes is equal to 40GHz. The carrier is removed by using a FBG. The output optical spectrum of FBG is shown in Fig. 10 as inset (ii). The two second-order sidebands are used as two parallel pumps. Because two pumps come from one laser, the pumps always have the same polarization direction and phase locked. The CW lightwave from another DFB laser at 1537.9nm is modulated by the second IM2 driven by 2.5Gbit/s electrical signal with a PRBS length of $2^{31}-1$ to generate regular NRZ optical signal.

The 2.5Gbit/s NRZ optical signals and two pump signals are combined by an OC before the EDFA. The optical spectra before and after the SOA are shown in Fig. 10 as inset (iii) and (iv), respectively. The SOA has 3-dB gain bandwidth of 68-nm, small signal fiber-to-fiber gain of 28-dB at 1552nm, polarization sensitivity smaller than 1dB, and noise figure of 6-dB at 1553nm. After the SOA, new up-converted signals are generated due to FWM, which is shown in Fig.10 as inset (iv). Then a tunable optical filter (TOF) with a bandwidth of 0.5nm is used to suppress the pump signals. The optical spectrum after the TOF is shown in Fig. 10

as inset (v). We can see that the converted and original signals are kept. The DSB signals with 80GHz frequency spacing between two converted sidebands are generated. In order to obtain the SSB signals, a 50/100 optical interleaver is used to remove one sideband. The optical spectrum after optical interleaver is shown in Fig. 10 as inset (vi). We can see that 2.5Gbit/s OOK signals are carried by the SSB-like signals with 40GHz frequency spacing between the converted signals and carrier, namely, the optical quadruple frequency mm-wave carried 2.5GHz signals is obtained. The power delivered to the fiber is 2dBm. After transmission over 20km SMF-28, the optical mm-wave is detected by O/E conversion via a photo-diode (PD) with a 3-dB bandwidth of 50 GHz. This scheme has some unique advantages such as polarization insensitive, high wavelength stability, and low-frequency bandwidth requirement for RF signal and optical components. 40GHz optical mm-wave SSB-like signal is generated by using 10GHz LO.

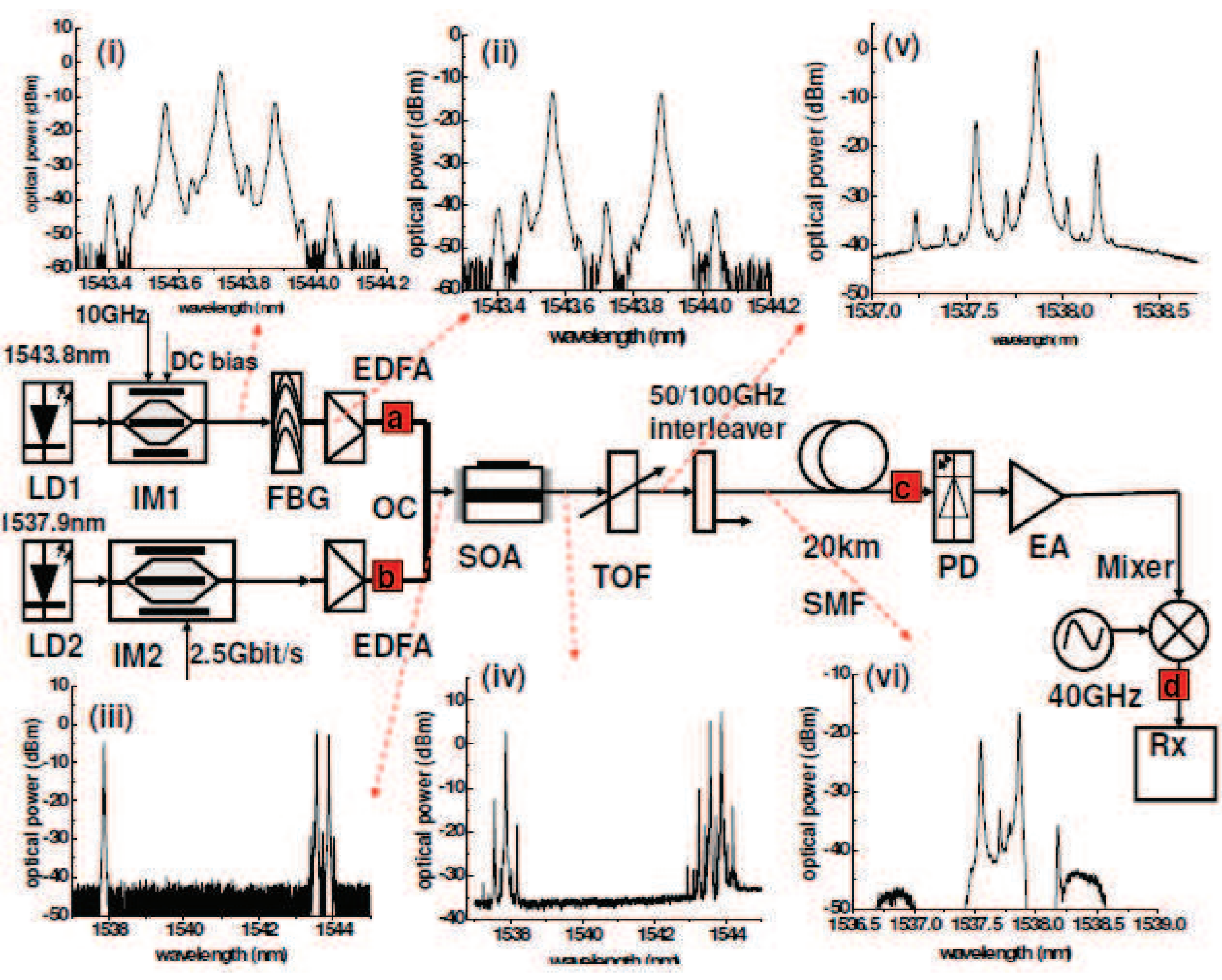


Fig. 10. Experimental setup and optical spectra for optical signal up-conversion. FBG: fiber Bragg grating. OC: optical coupler. SOA: semiconductor optical amplifier. TOF: tunable optical filter. EA: electrical amplifier. IM: intensity modulator. SSB: single sideband. DSB: double sideband. PD: photo-diode. BER: bit error ratio. EDFA: erbium-doped optical fiber amplifier.

In conclusion, we have obtained the following conclusions: (1) SOA can be used to generate high-repetitive mm-wave in ROF system; (2) we can use an IM to generate two pump instead of two independent DFB-LD, they may show good performance due to their phase-locked; (3) RoF system is polarization insensitive based on above mentioned method.

5. Conclusion

This chapter has theoretically and experimentally discussed the AOWC based on FWM effect in SOA for OFDM signals. The rules for OFDM signal is the same as that of regular OOK signal. We will investigate the FWM effect between the sub-carrier of OFDM signal which generate noise in the system in future. The application of SOA in RoF system has investigated. We experimentally proposed two polarization insensitive RoF systems. These schemes also have excellent advantages such as small size, high-gain, polarization insensitivity, and low-frequency bandwidth requirement for RF signal and optical components, and high wavelength stability.

6. Reference

[1] A. E. Kelly, D. D. Marcenac, and D. Nesset, "40 Gbit/s wavelength conversion over 24.6 nm using FWM in a semiconductor optical amplifier with an optimized MQW active region," *Electron. Lett.*, vol. 33, no. 25, pp. 2123-2124, Dec. 1997.

[2] W. Wang, H. N. Poulsen, L. Rau, H. F. Chou, J. E. Bowers, and D. J. Blumenthal, "Raman-enhanced regenerative ultrafast all-optical fiber XPM wavelength converter," *IEEE J. Lightw. Technol.*, vol. 23, no. 3, pp.1105-1115，Mar. 2005.

[3] J. Yu, X. Zheng, C. Peucheret, A. Clausen, H. Poulsen, and P. Jeppesen, "All-optical wavelength conversion of short pulses and NRZ signals based on a nonlinear optical loop mirror," *IEEE J. Lightw. Technol.*, vol. 18, no. 7, pp. 1007-1017, Jul. 2000.

[4] C. Porzi, A. Bogoni, L. Poti, and G. Contestabile, "Polarization and wavelength-independent time-division demultiplexing based on copolarized-pumps FWM in an SOA," *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 633-635, Mar. 2005.

[5] J. Yu, Z. Jia, Y. K. Yeo, and G. K. Chang, "Spectrally non-inverting wavelength conversion based on FWM in HNL-DSF and its application in label switching optical network," in *Proceedings of. 25th ECOC*, pp. 32–35,2005.

[6] J. Ma, J. Yu, C. Yu, Z. Jia, X. Sang, Z. Zhou, T. Wang, and G. K. Chang, "Wavelength conversion based on four-wave mixing in high-nonlinear dispersion shifted fiber using a dual-pump configuration," *IEEE J. Lightw. Technol.*, vol. 24, no. 7, pp. 2851-2858, Jul. 2006.

[7] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li and P. Hedekvist," Fiber-based optical parametric amplifiers and their applications," *JSTQE*, vol. 8, no. 3, pp. 506-520, May. 2002

[8] J. H. Lee, "All-optical signal processing devices based on holey fibers," *IEICE Trans. Electron.*, vol. E88-C, pp. 327–334, Mar. 2005.

[9] S. Radic and C. J. McKinstrie, "Optical Amplification and Signal Processing in Highly Nonlinear Optical Fiber," *IEICE Trans. Electron.*, vol. E88-C, pp. 859-869, May. 2005

[10] M. P. Fok, C. Shu and D. J. Blumenthal, "40-Gb/s polarization multiplexed RZ-DPSK signal wavelength conversion using a 32-cm bismuth-oxide nonlinear fiber." *CLEOE-IQEC*, 2007

[11] W. Astar, A. S. Lenihan, and G.M. Carter, “Polarization-insensitive wavelength conversion by FWM in a highly nonlinear PCF of polarization-scrambled 10-Gb/s RZ-OOK and RZ-DPSK signals,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1676-1678, Oct. 2007.

[12] S. Watanabe, S. Takeda, G. Ishikawa, H. Ooi, J. G. Nielsen, and C. Sonne, “Simultaneous wavelength conversion and optical phase conjugation of 200 Gbit/s (5x40 Gbit/s) WDM signal using a highly nonlinear fiber four-wave mixing,” *in the Proceedings of ECOE*, Paper TH3A1-4, pp. 1525–1529,1997.

[13] J. Yu, M.-F. Huang, Z. Jia, L. Chen, J.-G. Yu and G. K. Chang, “Polarization-nsensitive all-optical upconversion for seamless integration optical core/metro/access networks with ROF systems based on a dual-pump FWM scheme”, *IEEE J. Lightw. Technol.*, vol. 27, no. 14, pp.2605 – 2611, Jul. 2009.

[14] R. M. Jopson, and R. E. Tench, “Polarization- independent phase conjugation of lightwave signals,” *Electron. Lett.*, vol. 29, no. 25, pp. 2216-2217, Dec. 1993.

[15] K. Inoue, “ Polarization independent wavelength conversion using fiber four-wave mixing with two orthogonal pump lights of different frequencies.” *J. Lightwave Technol.*, vol. 12, no. 11, pp. 1916-1920, Nov. 1994.

[16] K. K. Y. Wong, M. Marhic, K. Uesaka, and L. Kazovsky, “Polarization-independent two-pump fiber-optical parametric amplifier.” *IEEE Photon. Technol. Lett.*, vol. 14, no. 7, pp. 911-913, Jul. 2002.

[17] S. Radic, C.J. Mckinstrie, R. M. Jopson, J. C. Centanni, Q. Lin and G. P. Agrawal, “ Record performance of parametric amplifier constructed with highly nonlinear fibre,” *Electron. Lett.*, vol. 39, no.11, pp. 838-839, May. 2003.

[18] Y. Wang, C. Y. Yu, T. Luo, L. S. Yan, Z. Q. Pan, and A. E. Willner, “Tunable all-optical wavelength conversion and wavelength multicasting using orthogonal polarized fiber FWM,” *IEEE J. Lightw. Technol.*, vol. 23, no. 10, pp. 3331-3338, Oct. 2005.

[19] J. Ma, J. Yu, C. Yu, and Z. Zhou, “Reducing polarization sensitivity for all-optical wavelength conversion of the optical packets based on FWM in HNL-DSF using co-polarized pump scheme,” *Opt. Commun.*, vol. 260, no.2, pp. 522-527, Nov. 2006.

[20] T. Hasegawa, K. Inouc, and K.Oda, “Polarization independent frequency conversion by fiber four-wave mixing with a polarization diversity technique,” *IEEE Photon. Technol. Lett.*, vol. 5, no.8, pp. 947-949, Aug. 1993.

[21] K. K. Y. Wong, M. Marhic, K. Uesaka, and L. Kazovsky,“ Polarization-independent one-pump fiber-optical parametric amplifier,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 11, pp. 1506-1508, Nov. 2002.

[22] K. Uesaka, K. K. Y. Wong, M. E. Marhic, and L. G. Kazovsky “Polarization-insensitive wavelength exchange in highly-nonlinear dispersion-shifted fiber,” *in the Optical Fiber Communications (OFC)*, (Anaheim, CA, 2002), Paper ThY3,2002.

[23] T. Tanemura, K. Katoh, and K. Kikuchi, “Polarization-insensitive asymmetric four-wave mixing using circularly polarized pumps in a twisted fiber,” *Opt. Express*, vol. 13, no. 19, pp. 7497-7505, Sep. 2005.

[24] K. Inoue, “Polarization effect on four-wave mixing efficiency in a single mode fiber,” *IEEE J. Quantum Electron.*, vol. 28, no. 4, pp. 883-894, Apr. 1992.

[25] J. Yu, X. Zheng, F. Liu, A. Buxens, and P. Jeppesen, "Simultaneous realization wavelength conversion and signal regeneration using nonlinear optical loop mirror," *Opt. Commun.*, vol. 175, no. 1, pp. 173-177, Feb. 2000.

[26] C. J. McKinstrie, H. Kogelnik, R. M. Jopson, S. Radic, and A. V. Kanaev, "Four-wave mixing in fibers with random birefringence," *Opt. Express*, vol. 12, no. 10, pp. 2033-2055, May. 2004.

[27] *M. Jinno,* "All optical signal regularizing/regeneration using a nonlinear fiber Sagnac interferometer switch with signal-clock walk-off," *IEEE J. Lightw. Technol.,* vol. 12, no. 9, pp. 1649-1659, Sep. 1994。

[28] J. Yu, P. Jeppesen, and S. N. Knudsen, "80 Gbit/s pulsewidth-maintained wavelength conversion based on a HNL DSF–NOLM including transmission over 80 km of conventional SMF," *Electron. Lett.*, vol. 37, no. 9, pp. 577-579, Jan. 2001.

[29] M. Jinno and M. Abe, "All-optical regenerator based on nonlinear fiber Sagnac interferometer," *Electron. Lett.*, vol. 28, no. 14, pp. 1350-1352, Jul. 1992.

[30] B. Mukhedee, "WDM optical Communication networks: progress and challengers, "*IEEE JSAC*, vol. 18, no. 10, pp: 1810-1824,Oct. 2000

[31] M. Kovacevic and A. Acampora, "Benefits of wavelength translation in all-optical clear-channel networks," *IEEE J Select Areas Commun,* , vol. 14, no. 5, pp. 868-880, Jun. 1996

[32] S. J. B. Yoo, "Wavelength conversion technologies for WDM network applications," *IEEE J. Lightw. Technol.*, vol. 14, no. 6, pp. 955-966, Jun. 1996

[33] K. Obermann, S. Kindt, D. Breuer, and K. Petermann, "Performance analysis of wavelength converters based on cross-gain modulationin semiconductor-optical amplifiers," *IEEE J. Lightw. Technol.* vol. 16, no. 1, pp. 78-85, Jan. 1998

[34] T. Durhuus, C. Joergensen , B. Mikkelsen , R. J. S. Pedersen, and K. E. Stubkjaer, "All optical wavelength conversion by SOA in a Mach-Zehnder configuration," *IEEE Photon Technol Lett,* vol. 6, no. 1, pp. 1044-1135, Jan.. 1994

[35] J. Yu, Z. Jia, Y. K. Yeo, and G. K. Chang, "Spectrally non-inverting wavelength conversion based on FWM in HNL-DSF and its application in label switching optical network, " *ECOC05*, pp. 32-35, 2009

[36] J. P. R. Lacey, M. A. Summerfield and S. J. Madden, "Tunability of polarization-insensitive wavelength converrs based on four-wave mixing in semiconductor optical amplifiers", *IEEE J. Lightw. Technol.,* vol.16, no. 12, pp. 2419-2427, Dec. 1998

[37] J. Lu, L. Chen, Z. Dong, Z. Cao, and S. C. Wen, "Polarization insensitive wavelength conversion based on orthogona pump four-wave mixing for polarization multiplexing signal in high-nonlinear fiber", *IEEE J. Lightw. Technol..*,vol.27, no. 34, pp. 5767-5774, Dec. 2009

[38] J. Lu, Z. Dong, L. Chen and J. Yu, "Polarization insensitive wavelength conversion based on four-wave mixing for polarization multiplexing signal in high-nonlinear fiber," *Opt. Commun.*, 282, pp.1274-1280, 2009

[39] L. James, A. Jean, "Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems," *Opt Express*, vol. 14, no. 6, pp. 2079-2084, Mar. 2006

[40] H. C. Bao, W. Shieh, "Transmission of wavelength-division-multiplexing channels with coherent optical OFDM," *IEEE Photon Technol Lett*, vol. 19, no. 12, pp. 922-924, Apr. 2007

[41] S. L. Jansen, I. Morita, T. C. W Schenk, N. Takeda, and H. Tanaka, "Coherent Optical 25.8-Gb/s OFDM Transmission Over 4160-km SSMF," *IEEE J. Lightw. Technol.*, vol. 26, no. 1, pp. 6-15, Jan. 2008

[42] L. Chen, J. Lu, Z. Dong, and J. Yu, "A radio-over-fiber system with photonics generated OFDM signals and wavelength reuse for upstream data connection," *In Proceeding of ICAIT*, Shenzhen, China, 1-3A-1, Aug. 2008

[43] J. Yu, "Novel radio-over-fiber configurations with centralized lightwave for uplink connection," in Signals, Systems and Electronics, 2007. ISSSE '07. International Symposium on. 2007, pp. 615-616, Jun.30-Aug. 2, 2007.

[44] L. Chen, Y. Shao, X. Lei, H. Wen, and S. Wen, "A novel radio-over-fiber system with wavelength reuse for upstream data connection," *IEEE Photon. Technol. Lett.,*, vol.19, no. 6, pp. 387-389, Mar. 2007..

[45] G. K. Chang, J. Yu, Z. Jia, and J. G. Yu, "Novel optical-wireless access network architecture for providing broadband wireless and wired services.".OFC 2006. Paper OFM1, Mar.5-10, 2006.

[46] J. Yu, Z. Jia,L. Yi, Y. Su, G. K. Chang, T. Wang, "Optical millimeter-wave generation or up-conversion using external modulators," *IEEE Photon. Technol. Lett.*, vol.18, no. 1, pp. 265-267, Jan. 2006.

[47] L. Chen, H. Wong, and S. Wen, "A radio-over-fiber system with a novel scheme for millimeter-wave generation and wavelength reuse for up-link connection," *IEEE Photon. Technol. Lett.*, vol.18, no. 19, pp.2056-2058, Oct. 2006.

[48] J. Yu, Z. Jia, T. Wang, and G. K. Chang, "Centralized lightwave radio-over-fiber system with photonic frequency quadrupling for high-frequency millimeter-wave generation," *IEEE Photon. Technol. Lett.*, vol.19, no. 19, pp. 1499-1501, Oct. 2007.

[49] J. He, L. Chen, Z. Dong, S, Wen, and J. Yu, "Full-duplex radio-over-fiber system with photonics frequency quadruples for optical millimeter-wave generation," *Optical Fiber Technology*, vol. 15, no. 3, pp.290-295, Jun, 2009.

[50] L. Liu, Z. Dong, Y. Pi, J. Lu, L. Chen, J. Yu, and S. Wen, "Radio-over-fiber system with frequency quadruple for millimeter-wave generation by external modulator," *Chinese Journal of Lasers*, vol. 36, no. 1, pp. 148-153, 2009.

[51] J. Lu, Z. Dong, L. Chen, J. Yu, and S. Wen, "High-repetitive frequency millimeter-wave signal generation using multi-cascaded external modulators based on carrier suppression technique," *Opt. Commun.*, vol. 281, no. 19, pp. 4889-4892, Oct. 2008.

[52] J. Lu, Z. Dong, Z. Cao, L. Chen, J. Yu, "All-optical Wavelength Conversion Based on Parallel Dual-pump Four-wave Mixing in Semiconductor Optical Amplifier for OFDM Optical Signal," *Acta Photonica Sinica*, vol. 38, no. 11, pp. 2857-2863, Nov. 2009.

[53] Z. Cao, Z. Dong, J. Lu, L. Chen, J. Yu, "All-optical Orthogonal2pump wavelength conversion of optical OFDM signal," *Journal of Optoelectronics ·Laser*, vol. 20, no.5, pp.622-627, May., 2009.

[54] J. Yu, J. Gu, X. Liu, Z. Jia and G. K. Chang,"Seamless integration of WDM-PON and wideband radio-over-fiber for 8 × 2.5Gb/s all-optical up-conversion using Raman-assisted FWM,"in Optical Communication," ECOC 2005,vol. 1, pp.80-90, 2005

[55] H. J. Song, J. S. Lee, and J. I. Song, "All-optical harmonic frequency up-conversion for a WDM radio over fiber system," *in Microwave Symposium Digest, 2004 IEEE MTT-S International*. pp. 405-407, Jun.6-11, 2004.

[56] Q. Wang, H. Rideout, F. Zeng, J. Yao, "Millimeter-wave frequency tripling based on four-wave mixing in a semiconductor optical amplifier," *IEEE Photon. Technol. Lett.,*, vol. 18, no.23, pp. 2460-2462, Dec. 2006.

[57] Q. Wang, F. Zeng, H. Rideout, J. Yao, "Millimeter-wave generation based on four-wave mixing in an SOA," *in Microwave Photonics, 2006. MWP '06. International Topical Meeting on*. pp. 1-4, Oct. 2006.

[58] T. Wang, M. Chen, H. Chen, and J. Zhang, "Millimeter-wave signal generation using two cascaded optical modulators and FWM effect in semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol.19, no.16, pp. 1191-1193, Aug., 2007.

[59] T. Wang, M. Chen, H. Chen, and S. Xie, "Millimeter-Wave Signal Generation Using Four-Wave Mixing Effect in SOA," OFC/NFOEC 2007, Anaheim,CA, pp.1-3, March 25-29, 2007.

[60] T. Wang, M. Chen, H. Chen, and S. Xie, "Millimetre-wave signal generation using FWM effect in SOA," *Electronics Letters*, vol. 43, no. 1, pp. 36-38, Jan., 2007.

[61] A. Wiberg, P. Millan, M. Andres, and P. Hedekvist, "Microwave-photonic frequency multiplication utilizing optical four-wave mixing and fiber Bragg gratings," *IEEE J. Lightw. Technol.* vol. 24, no.1, pp.329-334, Jan. 2006.

[62] C. T. Lin, P.T. Shih, J. Chen, W. Xue, P.Peng and S. Chi, "Optical millimeter-wave signal generation using frequency quadrupling technique and no optical filtering," *IEEE Photon. Technol. Lett.,* vol. 20, no. 12, pp.1027-1029, Jun. 2008.

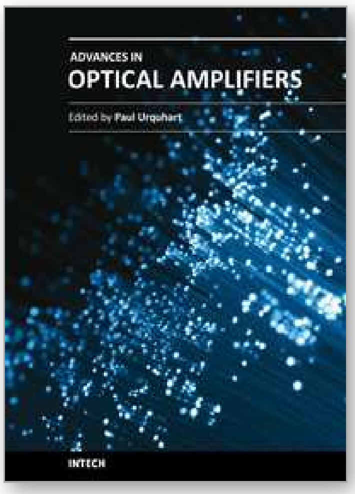
[63] P. T. Shih, J. Chen, C. T. Lin, W. Jiang, H. Huang, P. Peng and S. Chi, "Optical millimeter-Wave signal generation via frequency 12-tupling," *IEEE J. Lightw. Technol.*, vol.28, no.1, pp. 71-78, Jan. 2010.

[64] H. Kim, H. Song, J. Song, "All-optical frequency up-conversion technique using four-wave mixing in semiconductor optical amplifiers for radio-over-fiber applications," *in Microwave Symposium, 2007. IEEE/MTT-S International.* Honolulu, HI, Jun. 3-8, pp. 67-70, 2007.

[65] J. Lu, Z. Dong, Z. Cao, L. Chen, S. Wen, and J. Yu, "Polarization insensitive all-optical up-conversion for ROF systems based on parallel pump FWM in a SOA," *Opt. Express,* vol. 17. no.9, pp.6962-6967, Apr. 2009

[66] Z. Dong. Z. Cao, J. Lu, L. Chen, S. Wen, Z. Jia, and G. K. Chang, "All-optical up-conversion of millimeter-wave signals for ROF system using optical carrier suppression-based dual-pump FWM in an SOA," in Optical Fiber Communication - incudes post deadline papers, *OFC 2009,* San Diego, CA, pp. 1-3, Mar. 22-26, 2009.

[67] J. Yu, M. Huang, Z. Jia, T. Wang, G. K. Chang, "A Novel Scheme to Generate Single-Sideband Millimeter-Wave Signals by Using Low-Frequency Local Oscillator Signal," *IEEE Photon. Technol. Lett.* Vol. 20, no.7,pp. 478-480, Apr. 2008.



Advances in Optical Amplifiers

Edited by Prof. Paul Urquhart

ISBN 978-953-307-186-2

Hard cover, 436 pages

Publisher InTech

Published online 14, February, 2011

Published in print edition February, 2011

Optical amplifiers play a central role in all categories of fibre communications systems and networks. By compensating for the losses exerted by the transmission medium and the components through which the signals pass, they reduce the need for expensive and slow optical-electrical-optical conversion. The photonic gain media, which are normally based on glass- or semiconductor-based waveguides, can amplify many high speed wavelength division multiplexed channels simultaneously. Recent research has also concentrated on wavelength conversion, switching, demultiplexing in the time domain and other enhanced functions. Advances in Optical Amplifiers presents up to date results on amplifier performance, along with explanations of their relevance, from leading researchers in the field. Its chapters cover amplifiers based on rare earth doped fibres and waveguides, stimulated Raman scattering, nonlinear parametric processes and semiconductor media. Wavelength conversion and other enhanced signal processing functions are also considered in depth. This book is targeted at research, development and design engineers from teams in manufacturing industry, academia and telecommunications service operators.

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821