Improvement of four-wave mixing-based wavelength conversion efficiency in dispersion shifted fiber by 40-GHz clock pumping

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40-GHz clock modulated signal as a pump to improve the efficiency of four-wave mixing (FWM)-based wavelength conversion in a 26.5-km dispersion shifted fiber (DSF) is investigated. The experimental results demonstrate that the conjugated FWM component has higher intensity with the clock pumping than that with the continuous-wave (CW) light pumping. The improvement of FWM-based wavelength conversion efficiency is negligible when the pump power is less than Brillouin threshold. But when the pump power is greater than Brillouin threshold, the improvement becomes significant and increases with the increment of pump power. The improvement can increase up to 9 dB if pump power reaches 17 dBm.

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All optical wavelength conversion (AOWC) is critical to future optical networks as it can improve the wavelength utilization and reduce the network blocking probability[1]. Different schemes have been researched on AOWC, such as utilizing semiconductor optical amplifier (SOA)[2], electro-absorption (EA) modulator[3], and highly nonlinear fibers. AOWC based on four-wave mixing (FWM) in the highly nonlinear fibers has been extensively researched because of its attractiveness as a passive device[4,5]. But its performance is limited to the relatively lower conversion efficiency compared with SOA or EA modulator. The lower efficiency is attributed to both the low nonlinear effect in optical fibers and the stimulated Brillouin scattering (SBS) depletion of pump power when the continuous-wave (CW) light is used as a pump. Fortunately, the clock modulated signal as the pump shows great advantage over the CW light pump, which greatly suppresses the SBS process and major part of the pump power is contributed to the nonlinear process such as self-phase modulation (SPM), cross-phase modulation (XPM), and FWM. It foresees that FWM-based wavelength conversion efficiency in optical fibers can be improved if clock signal is used as the pump. A proof-of-concept experiment shows that up to 9-dB conversion efficiency can be obtained by 40-GHz clock pumping in a 26.5-km dispersion shifted fiber (DSF).

The proof-of-concept experimental setup is shown in Fig. 1. The CW light centered at f_{pump} is phase modulated by a 40-GHz clock signal. The probe signal is another CW light centered at f_{probe}. The DSF length is 26.5 km with nominal loss of 7.6 dB. Limited by the output power of laser source, the power of clock modulated signal is about -4.3 dBm. For the convenience of comparison with clock pumping, the CW light at f_{pump} launched into erbium-doped fiber amplifier (EDFA) is also set to be -4.3 dBm by an attenuator when used as the pump. The maximum output power of EDFA is about 21 dBm. The power of probe signal is set to be 0 dBm. The optical spectrum analyzer (OSA) is used to monitor the output spectrum of DSF. The tunable optical band-pass filter (OBPF) is used to filter out the conjugated FWM component centered at $2f_{\text{pump}} - f_{\text{probe}}$.

Figure 2(a) shows the forward output spectra of DSF, where the input power of the pump light co-propagating with the probe signal is 15 dBm and the center wavelengths of the pump and probe light are 1552.54 and 1553.58 nm respectively. With the clock pumping, the conjugated FWM component has about 10-dB intensity higher than that with the CW light pumping, and the output spectrum broadens. The reason is explained by Fig. 3. The forward and backward output powers of the DSF are compared when only the clock pump light or CW pump light launched to it. The forward output power is lower than the backward output power for the CW pump
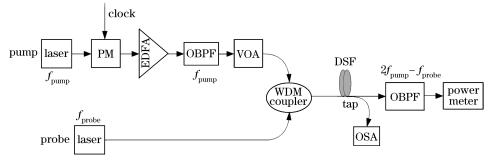

Fig. 1. Proof-of-concept experimental setup for FWM-based wavelength conversion using clock pumping. PM: phase modulator; WDM: wave division multiplexing; VOA: variable optical attenuator.
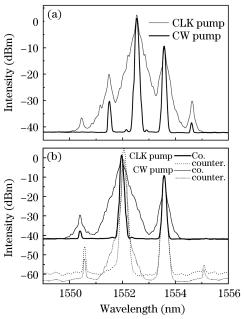
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Fig. 2. DSF output spectra at the side opposite to probe signal. Co.: co-propagating pumping; Counter.: counter-propagating pumping. (a) Co-propagating pumping, $\lambda_{\text{pump}} = 1552.54$ nm, $\lambda_{\text{probe}} = 1553.58$ nm; (b) $\lambda_{\text{pump}} = 1551.96$ nm, $\lambda_{\text{probe}} = 1553.58$ nm.
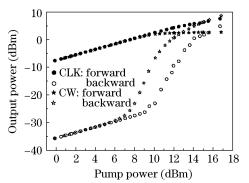

Fig. 3. Forward and backward output powers of the DSF with only pump light launched to it. CLK: 40-GHz clock pump light; CW: CW pump light.

if the power launched into DSF is increased beyond 13 dBm, indicating that most of the CW light pump power is depleted by SBS process and converted to the backward light. On the other hand, the forward output power is higher than the backward output power for the clock pump even the power launched to DSF is up to 17 dBm. This is because that the SBS process is greatly quenched with the clock pump light, so the most power of the pump light can contribute to other nonlinear effects such as SPM, XPM, and FWM. The former two will lead the spectrum to broaden for both pump and probe signals, and FWM generates the new frequency components centered at 1551.50 and 1554.64 nm. It can be clearly seen from Fig. 3 that the forward output power for the clock pump is higher than that for the CW light pump if the input power to DSF is greater than 10 dBm, so the FWM components has much higher intensity with the clock pumping. In Fig. 2(a), we also notice that another new frequency component centered at 1550.46 nm for the clock pump, which is generated due to the

2nd-order FWM interaction between the 1st-order conjugated FWM component at 1550.42 nm and pump light at 1552.54 nm. It means that high-order FWM frequency component will be generated because of the higher intensity of 1st-order FWM component by the clock pumping, which should be avoided in the wavelength conversion application. Therefore we remove the high-order FWM component by increasing the wavelength spacing between pump and probe lights. Figure 2(b) shows the measurement result with the pump centered at 1551.96 nm. The intensity of FWM conjugated component at 1550.42 nm is also as high as 10 dB for the clock pump. But the idler component at 1555.20 nm is negligible because of the increased wavelength spacing and the intensity-dependent phase matching. Fortunately it is seldom used in the wavelength conversion. Then we also measure the output spectrum with the counter-propagation pumping as the dotted lines shown in Fig. 2(b). The probe signal nonlinearly interacts with the backward light of the pump signal, but the intensity of FWM components is much lower compared to that with co-propagating pumping. It is explained that FWM is a phase matching process and the backward Stokes light is much of phase noise, which greatly decreases the conversion efficiency.

Finally, we measure the improvement of FWM-based wavelength conversion efficiency with clock pumping over CW pumping. To define the improvement as the ratio of the wavelength conversion efficiency for the clock pumping to that for the CW pumping, it can be expressed as $\eta_{\text{clock pump}}/\eta_{\text{CW pump}}$. Here $\eta_{\text{clock pump}}$ and $\eta_{\text{CW pump}}$ are the conversion efficiencies for the FWM conjugated component with clock pumping and CW pumping respectively, and the conversion efficiency is the ratio of the converted signal power to the input probe signal. The result in Fig. 4 indicates that the improvement is negligible when the pump power is less than 10 dBm, i.e., the Brillouin threshold as predicted in Ref. [6]. But when the pump power is greater than about 11 dBm, the improvement becomes significant and increases with the increment of pump power. When pump power reaches 17 dBm, the improvement increases to about 9 dB.

It is desirable to improve the FWM-based wavelength conversion efficiency in optical fibers. In this paper, we experimentally demonstrate the improvement of conversion efficiency with 40-GHz clock and co-propagating pumping in 26.5-km DSF. Up to 9-dB improvement over CW light pumping can be achieved with the pump power of 17 dBm.
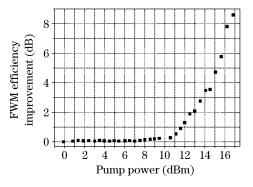

Fig. 4. FWM-based wavelength conversion efficiency improvement of clock pumping over CW pumping.

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