LETTER

Multi-Stage Wavelength Conversion by Cascaded SSB Modulators

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SUMMARY We present the first demonstration of multiple-stage wavelength conversion using cascaded $LiNbO_3$ Mach-Zehnder SSB modulators. Wavelength is accurately shifted by 18 GHz at each stage. 72 GHz frequency shift with the relative intensity noise (RIN) value of −144.5 dB/Hz is achieved by four stages. The achieved equivalent noise figure is 7.5 dB.
key words: *optical single sideband, wavelength conversion*

1. Introduction

Wavelength conversion is one of the key functions of wavelength division multiplexed (WDM) optical networks. Several techniques and applications have been studied over the past few decades [1]–[3].

Wavelength conversion by using a $LiNbO_3$ Mach-Zehnder single-sideband (SSB) modulator is one of the strong candidates [4]–[10]. The optical SSB modulator performs a roll of wavelength conversion when the optical carrier is suppressed. The converted wavelength can be set accurately by using electrical signal generator of continuous sinusoidal wave. The wavelength span from the original wavelength to the converted wavelength is inherently equal to the input signal frequency of the electrical signal generator.

Other methods of semiconductor optical amplifier (SOA) based conversion or opto-electric conversion need a pump light source or conversion light source. Optical SSB based conversion, however, needs neither. Hence, optical SSB based conversion can yield much simpler configurations. In addition, optical SSB based conversion basically retains the coherency of the input signal light. SOA based conversion or opto-electric conversion requires care to ensure the coherency of the pump light source or conversion light source.

This paper shows the first experiment to demonstrate cascaded wavelength conversion by using four $LiNbO_3$ Mach-Zehnder SSB modulators. The wide converted wavelength of 72 GHz and the low relative intensity noise (RIN) of −144.5 dB/Hz have been achieved.

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2. Experimental Setup

The experimental setup is shown in Fig. 1. A laser set at the wavelength of 1558.98 nm was used as a continuous wave source. The laser light was continuously input to the wavelength converter system. We cascaded four wavelength converters to investigate the impact of cascading on performance. The outputs of each wavelength converter were input to an optical spectrum analyzer or relative intensity noise (RIN) measurement system.

Each wavelength converter consisted of a polarization controller, a $LiNbO_3$ Mach-Zehnder SSB Modulator, erbium doped fiber amplifier (EDFA), 90° hybrid coupler and so on, see the upper side of Fig. 1. The optical input was adjusted by a polarization controller, shifted to an upper frequency in the SSB modulator, and then amplified by the EDFA to compensate the loss of the modulator. The electrical continuous sinuoidal wave of 18 GHz was divided and then input to the $LiNbO_3$ Mach-Zehnder SSB Modulators.

The optical input level to the SSB modulator was set at +13 dBm. $V\pi$ of the modulators ranged from 2.7 V to 2.8 V. The electrical power supplied to each arm of the $LiNbO_3$ Mach-Zehnder SSB modulator was set about at +21 dBm/+15 dBm via a 50 ohm system to evaluate drive voltage dependency. These output optical amplitude levels correspond to 83% and 49% of the theoretical maximum optical amplitude as calculated from the level of the third harmonic.

3. Results and Discussion

Figure 2 shows the optical spectrum from the wavelength

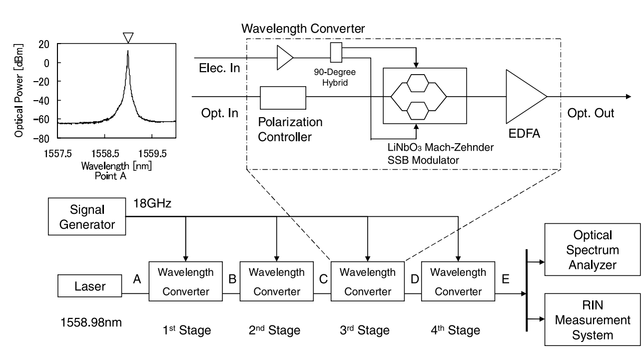

Fig. 1 Experimental setup.

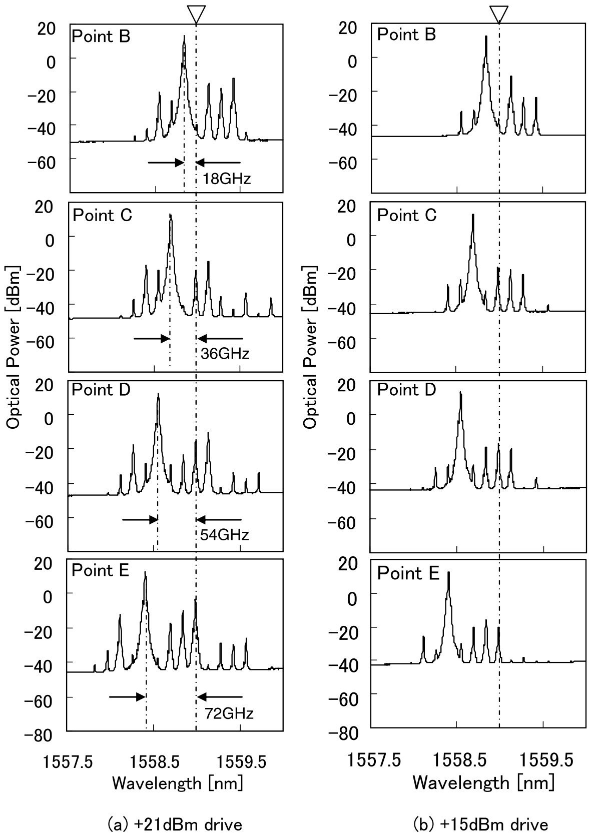

Fig. 2 Optical spectrum of wavelength converter outputs.

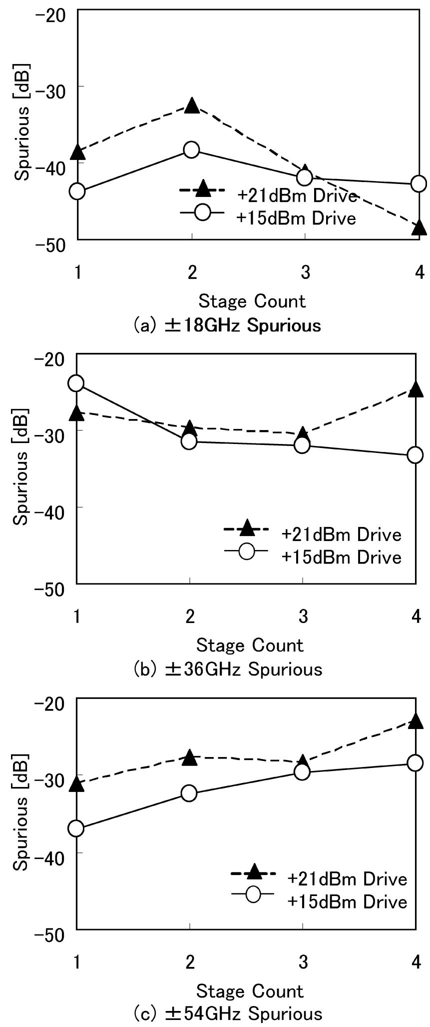

Fig. 3 Optical desired to spurious signal ratio.

converters. The resolution bandwidth of the spectrum was 0.01 nm. The inversed triangles indicate the wavelength of the original laser source. Points A − E of Fig. 2 correspond to A − E of Fig. 1. As the light passed through each stage, its wavelength was lowered; noise level increased gradually due to the noise of the EDFAs in the wavelength converters. The converter accurately shifted the wavelength by 18 GHz in each stage. Total amount of 72 GHz frequency shift was achieved with four stages.

The ratios of spurious signal to the converted signal, i.e., the desired signal, in the optical signal are shown in Fig. 3. The ratios of the spurious signals on both sides (plus and minus) are plotted. The spurious signal levels of ±18 GHz were always low, compared to other spurious signal components. It is interesting that the spurious signal level of the −18 GHz point (the nearest spurious signal component just to the left of the desired signal) was also suppressed at point C at later points even though the prior stage converter already generated a spurious signal component corresponding to the point of +18 GHz. Therefore, it is easy to insert an optical filter for obtaining a purer converted desired wavelength.

The optical input powers to the SSB modulators were +13 dBm, and the optical output powers from the SSB modulators were about +2 dBm and −4 dBm for the modulation drive powers of +21 dBm and +15 dBm, respectively. This means that each SSB modulator worked as an attenuator. The conversion losses of the SSB modulators were calculated to be about −11 dB and −17 dB, respectively, for the modulation drive power levels. The EDFA compensated these conversion losses.

SSB modulators did create the loss, but not the noise. On the other hand, EDFAs, compensated the loss and created noise at the same time. Therefore, the noise characteristics of wavelength conversion are determined by the EDFA's noise. Figure 4 shows the measured RIN values with +21 dBm drive and +15 dBm drive. Measured noise levels increased with the increase in stage count number and a decrease in the drive power. At the point of 1 GHz, we recorded −144.5 dB/Hz with +21 dBm drive and −137.7 dB/Hz with +15 dBm drive.

We calculated the achieved noise figure from

$$NF = (RIN_{out} - RIN_{in})\frac{P_{in}}{2h\nu}, \tag{1}$$

where NF is the noise figure, RIN_{out} and RIN_{in} is the RIN of the output and the input of the converter, P_{in} is the input optical power to the EDFA in the converter, h is Planck's constant, ν is the light's frequency [11]. The average noise

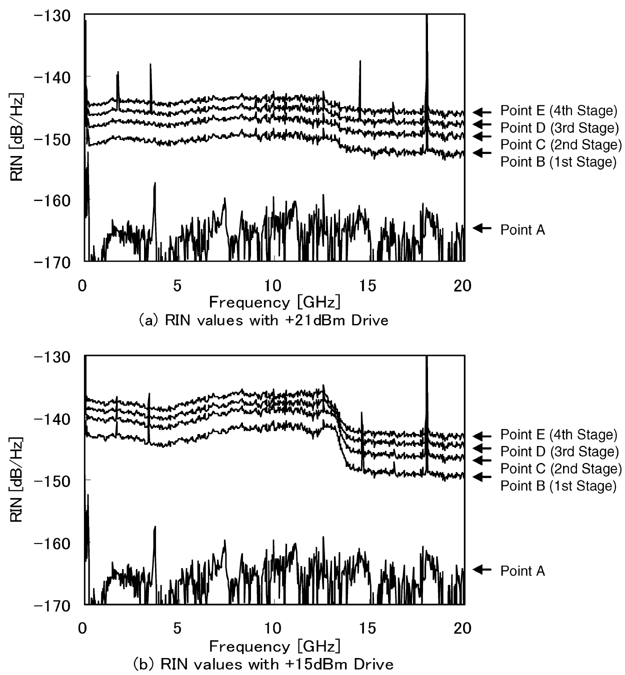

Fig. 4 Relative intensity noise values.

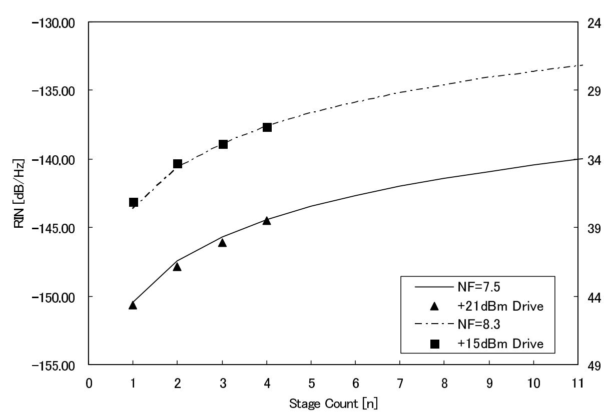

Fig. 5 RIN values (Q values) versus stage count.

figures of +21 dBm / +15 dBm driven converters at the point of 1 GHz RIN values are 7.5 dB and 8.3 dB, respectively.

Figure 5 shows the measured and calculated RIN values of the nth stage. The calculated values are derived using

$$RIN_n = \frac{2h\nu \cdot n \cdot NF}{P_{in}}, \tag{2}$$

where n is the stage count, and RIN_n is the RIN values of nth stage [12]. The RIN differences between +21 dBm and +15 dBm drive are about 6.8 dB. The vertical axis on the right shows Q values corresponding to the RIN values. Q value is determined by

$$Q = \frac{\sqrt{SNR}}{2} \tag{3}$$

$$SNR = \frac{1}{\int_0^B RIN(f)df} = \frac{1}{B \cdot RIN} \tag{4}$$

where B is the noise bandwidth and SNR is the signal-to-noise ratio, neglecting the influences of shot noise and thermal noise generated at the receiver. Q factor indicates the quality of the eye opening of the optical digital signals [13], [14]. For instance, the Q factor value of 15.6 dB corresponds to the bit error rate of 10^{-9} (SNR = 21.6 dB). We assumed B was 10 GHz for 10 Gbps digital signal transmission, and that the RIN value was constant against frequency.

In the calculation, the RIN value of −140 dB/Hz (Q value of 34 dB) is achieved at the 11th stage (+21 dBm drive)/2nd stage (+15 dBm drive), and the RIN value of −130 dB/Hz (Q value of 24 dB) is recorded at the 110th stage (+21 dBm drive)/23rd stage (+15 dBm drive). These noise levels are low confirming that cascaded wavelength conversion is feasible for practical use.

4. Conclusion

We have conducted the first experiment of cascaded wavelength conversion by using four $LiNbO_3$ Mach-Zehnder SSB modulators with the wide converted wavelength of 72 GHz and the low relative intensity noise (RIN) of −144.5 dB/Hz. The converter accurately shifted the wavelength by 18 GHz in each stage. In total, 72 GHz frequency shift was achieved with four stages. The spurious level and noise level (RIN) were measured, and the multi-stage RIN values were calculated up to 110th stages; all results confirmed the practicality of the proposal.

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