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# Characteristics of selective and tunable wavelength converters using quasi-phase matched lithium niobate waveguide devices with dual pump configuration

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## ABSTRACT

We report selective and tunable wavelength converters (STWCs) from an arbitrary wavelength to another arbitrary one, which employ the cascaded second-order nonlinear effect of sum frequency mixing (SFM) and difference frequency mixing (DFM) in quasi-phase matched (QPM) lithium niobate (LN) waveguide devices. Through wavelength conversion experiments using short optical pulses for the QPM-LN waveguide devices having different crystal length, we investigate bandwidth limitation of the QPM-LN-based all-optical STWCs with dual pump configuration. We show that the critical pulse width to be wavelength-converted without waveform distortion is proportional to the length of the LN crystal, and also reveal that those ratio is 1.6 ps/cm. By utilizing this critical value as a performance metric, we successfully demonstrate highly efficient selective and tunable wavelength conversion of 40-Gbit/s data signals using the SFM–DFM cascade in a QPM-LN waveguide device with an optimum crystal length of 5 cm. The 5 cm-long device can be applied to channel-by-channel wavelength conversion in 100-GHz-spaced 40-Gbit/s dense wavelength-division multiplexed systems.

## 1. Introduction

All-optical wavelength converters can realize various functions such as optical add-drop multiplexing, optical channel routing, optical label processing, optical phase conjugation, and dynamic light-path establishment for constructing transparent and scalable wavelength-division multiplexed (WDM) networks or future optical packet switched systems. The potential of such wavelength converters has already been revealed in a number of experimental demonstrations and system experiments [1–4].

To date, the cascaded $\chi^{(2)}$ effect of second harmonic generation (SHG) and difference frequency mixing (DFM) in quasi-phase matched (QPM) $LiNbO_3$ (LN) waveguide devices has realized highly efficient and extra-broadband wavelength conversion in the optical communication band at 1550 nm [5–14]. The QPM-LN waveguide devices that employ the maximum nonlinear optical tensor element $d_{33}$ of the LN crystal can produce various functions based on frequency mixing. The SHG–DFM cascade is almost equivalent to four-wave mixing in the third-order nonlinear devices such as optical fibers and semiconductor optical amplifiers, which can realize many kinds of all-optical signal processing [15–25]. The $d_{33}$-using QPM-LN waveguide devices have excellent features such as ultra-fast response, low noise, high efficiency, low cost, compactness, integration compatibility, and high stability. In addition, the QPM wavelength can be arbitrarily controlled by the period of the $\chi^{(2)}$ grating. When the wavelength of a continuous-wave (CW) pump light is set around the QPM wavelength, its second harmonic (SH) is first generated; DFM between the CW SH pump light and the signal light then produces the wavelength-converted or phase-conjugated signal light. As a result, this single-pumped wavelength conversion technique is independent of both the modulation format and the bandwidth of original signal to be wavelength-converted. However, the wavelength of the wavelength-converted signal light is determined compliantly, once the wavelength of the original signal light is given. Furthermore, the CW pump wavelength must be precisely set to the QPM wavelength for maintaining high wavelength conversion efficiency on account of the QPM bandwidth limitation of the device. The QPM bandwidth narrows almost in inverse proportion to the device length. For example, the QPM bandwidth of the 5 cm-long $d_{33}$-using QPM-LN waveguide device is as narrow as 60 GHz.

Meanwhile, a selective and tunable wavelength converter (STWC) using the cascaded $\chi^{(2)}$ effect of sum frequency mixing (SFM) and DFM in a QPM-LN waveguide device, where the wavelengths of two CW pump lights are tuned depending on the wavelengths of the original signal

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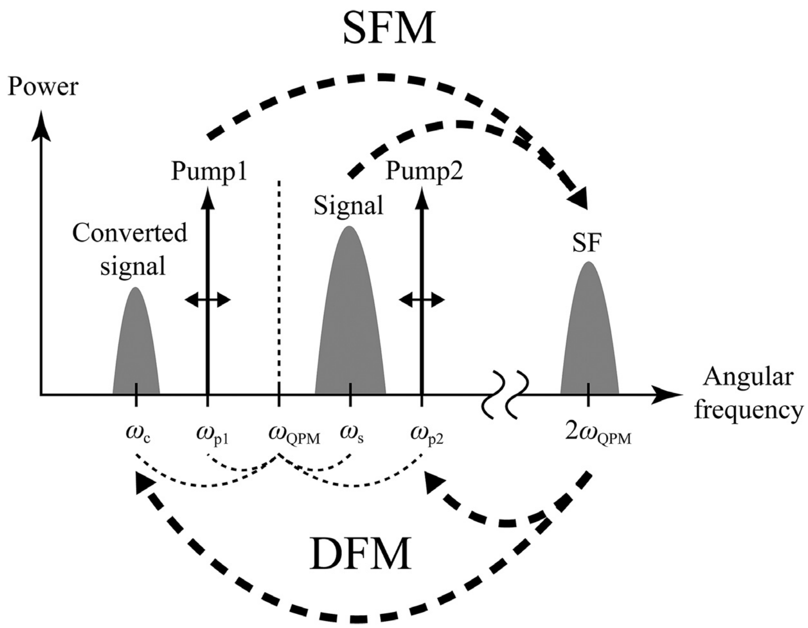

**Fig. 1.** Operation principle of selective and tunable all-optical wavelength conversion using quasi-phase matched lithium niobate devices.

(target wavelength-channel) and the wavelength-converted signal, has also been proposed [26]. The operation principle in the frequency domain is illustrated in Fig. 1. In this wavelength conversion technique with a dual pump configuration, a signal (target) light and two CW pump lights 1 and 2, which have angular frequencies $\omega_s$, $\omega_{p1}$, and $\omega_{p2}$, respectively, are launched on the QPM-LN waveguide device with a QPM frequency of $\omega_{QPM}$; in order to satisfy the QPM condition, $\omega_{p1}$ is adjusted to $2\omega_{QPM} - \omega_s$; SFM between the target signal light and the CW pump light 1 then produces a sum-frequency component at a frequency of $2\omega_{QPM}$; a wavelength-converted signal ($\omega_c$) is finally produced at a frequency of $2\omega_{QPM} - \omega_{p2}$ through DFM between the $2\omega_{QPM}$ frequency component and the CW pump light 2. Using the QPM-LN waveguide devices, selective and tunable wavelength conversion from an arbitrary wavelength to another arbitrary one is thus achieved by changing the pump frequencies $\omega_{p1}$ and $\omega_{p2}$ appropriately. Such a dual-pumped scheme has been applied to the QPM-LN-based STWCs for short optical pulses [27] and several modulation formats of the optical signals [28,29], and its effectiveness has been confirmed.

Generally, the wavelength conversion efficiency of the QPM-LN waveguide devices or the output power of the wavelength-converted signal light increases dramatically as the length of the LN crystal becomes longer. In such a dual-pumped wavelength conversion scheme, however, the available signal bandwidth might be strictly limited by a bandwidth for the cascaded $\chi^{(2)}$ process of SFM and DFM [30–32]. In other words, the crystal length of the QPM-LN waveguide device has to be optimally determined so that the bandwidth for the SFM–DFM combined process corresponds to or is slightly broader than the bandwidth of the original signals to be wavelength-converted. Each bandwidth for the SFM process and the DFM process is compatible with the QPM bandwidth of the device. However, the bandwidth for the cascaded $\chi^{(2)}$ process of SFM and DFM can be only roughly estimated from the QPM bandwidth due to the complexity of those combined processes. It is still an open question how the waveform of the wavelength-converted signal is affected by such SFM–DFM combined bandwidth and how broad the available signal bandwidth is.

In this paper, we experimentally investigate characteristics of all-optical STWCs employing the SFM–DFM cascade in the $d_{33}$-using QPM-LN waveguide devices. Through wavelength conversion experiments using short optical pulses for the devices having different length of the LN crystals, we reveal that the critical pulse width to be wavelength-converted without pulse broadening is proportional to the crystal length, and the value of these ratio is 1.6 ps/cm. We also show that this critical value can be utilized as a performance metric for such dual-pumped QPM-LN-based STWCs. Based on the metric, we realize a highly efficient STWC for 40 Gbit/s data signals employing a QPM-LN waveguide device with an optimum crystal length of 5 cm. Measured conversion efficiency from an arbitrary wavelength to another arbitrary one is as high as −10 dB. Thus, the 5 cm-long device is very attractive for channel-by-channel wavelength conversion in 40 Gbit/s dense WDM (DWDM) networks thanks to many excellent features such as wide wavelength tunability, high conversion efficiency, modulation format free, adequate signal bandwidth, and selectivity of 100 GHz-spaced DWDM signals.

## 2. Bandwidth limitation and performance metric of QPM-LN devices

In this section, we first investigate performance limitation of the dual-pumped all-optical STWCs employing the SFM–DFM cascade in the QPM-LN waveguide devices. Based on the experimental results, we then propose a performance metric for such QPM-LN-based STWCs.

### *2.1. Experimental setup for measuring basic characteristics*

The schematic diagram of the experimental setup is shown in Fig. 2. Two CW pump lights 1 and 2 were produced by tunable laser diodes LD1 and LD2, respectively. A tunable bismuth-based mode-locked laser source (MLLS) driven at a modulation frequency of 10 GHz produced original signal pulses to be wavelength-converted with a sech$^2$ intensity waveform whose temporal pulse width was about 1.0 ps over the entire tunable wavelength range [33–36]. The full width at half-maximum of the original signal pulses $T_s$ was appropriately varied by changing the bandwidth of an optical bandpass filter (BPF).

The two CW pump lights combined by an optical fiber coupler and the filtered original signal pulses to be wavelength-converted were pre-amplified by erbium-doped fiber amplifiers (EDFAs), respectively. After combined through an optical fiber coupler, they were launched on QPM-LN waveguide devices. The powers of the CW pump lights 1 and 2, and the average power of the original signal pulses launched on the QPM-LN waveguide devices were 18.7 dBm, 19.9 dBm, and 11.2 dBm, respectively.

We investigated characteristics of three QPM-LN waveguide devices having the crystal lengths (interaction lengths for the $\chi^{(2)}$ effect) of 1 cm,