Tunable Wavelength Converter and Filter Based on Periodically Poled Lithium Niobate

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In this paper, we present our researches on the applications of periodically poled lithium niobate (PPLN) in optical communications. Tunable wavelength converter and filter are investigated based on PPLN with unique features which show potential applications in next generation all-optical networks.

Key Words: Periodically poled lithium niobate, Wavelength converter, Wavelength filter.

1. Introduction

Ferroelectric crystals are important materials in many kinds of applications. Since the invention of so called quasi-phase matching technique, periodically domain-inverted ferroelectrics crystals with modulated second order nonlinear susceptibility are widely used in frequency conversion application. In periodically domain-inverted ferroelectrics crystals, besides the nonlinear optical coefficients, other third-rank tensors, such as the electro-optic (EO) coefficient, are also modulated periodically because of the periodically reversed ferroelectric domains. This periodically modulation of the EO coefficient also brings some novel applications. In this paper, tunable wavelength converter and filter are investigated based on periodically poled lithium niobate are investigated.

2. Solc-type wavelength filter

2.1 Principles

When an electric field is applied along the Y axis of a crystal with 3m symmetry, the new index ellipsoid deforms to make its principal axes rotated at an angle θ about the x axis with respect to the unperturbed principal axes. Since θ is proportional to the product of the electric field and the electro-optic coefficient, when an uniformed electric field applying along the Y axis of the crystal, the rotation angle of the original domain is opposite to that of the inverted domain because of the reversal of the spontaneous polarization. Thus, in a periodically domain inverted crystal with a uniformed electric field applied along the Y axis, a structure with alternating left and right rotation angle θ will be formed due to the periodic EO coefficient. This structure is similar to the well known folded Solc filter structure with alternating azimuth angles of the crystal axes. So we call it Solc layered structure.

Fig.1 shows the schematic diagram of a Solc layered structure based on electro-optic periodically domain inverted crystals. X, Y and Z are the principal axes of the unperturbed index ellipsoid. Λ is the period of this structure. N is the period number. The arrows inside the structure indicate the spontaneous polarization directions. When an

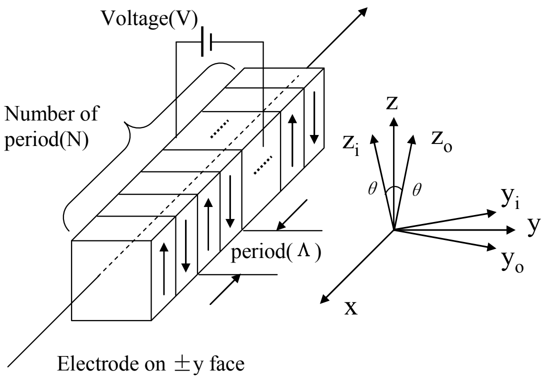

Fig.1 Schematic diagram of a Solc layered structure based on electro-optic periodically domain inverted crystals

electric field is applied along the Y axis, the index ellipsoid deforms. $Y_{o,i}$ and $Z_{o,i}$ are the new perturbed principal axes of the original domain and the inverted domain, respectively.

2.2 Device of tunable Solc-type filter

In 2003, we demonstrated a Solc filter based on PPLN operating in the optical communication wavelength range.[1)] Similar to the traditional folded type Solc filter, a PPLN crystal was placed between two crossed polarizers. This sample is with dimensions of 28 mm × 5 mm × 0.5 mm consists of four gratings with periods from 20.2 to 20.8μm and a width of 1 mm. A measured transmission power versus wavelength for 20.6μm and 20.8μm period PPLNs is shown in Fig.2. A typical transmission spectrum of traditional Solc filter can be seen in this figure. The amplitude modulation of the transmission power by applying an electric voltage along the Y axis of the PPLN was observed. Also a voltage offset is observed. The transmission of the power is about 70% with a 0V applied field in this application.

In the experiments, we also found that, without field applied, the device also has the function of Solc filter,[2)] although the theory said it hasn't. We suggest that the photovoltaic effect (PVE) plays an essential role in the performance of non-field

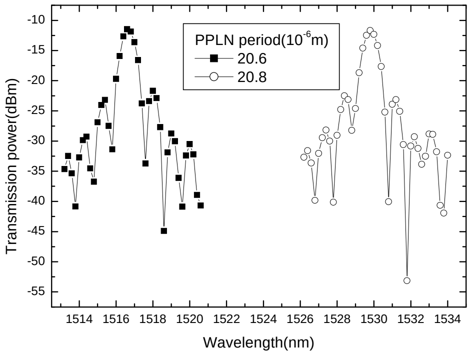

Fig.2 Measured transmission power versus wavelength for 20.6μm and 20.8μm period PPLNs

applied PPLN Solc filter.[3] Both the theory and the experiment show that the PVE play an important role in the formation of the Solc wavelength filter without external applied field. The PVE effect sometimes can not be neglected, especially in electric-optic devices. On the other hand, we can use this effect to build the light controlled optical devices or to measure the PVE coefficients. Fig. 3 shows measured output power against wavelength for the PPLN of period 20.8μm with and without the illumination of the UV light, respectively. The UV light intensity is about 143mw/cm^2. The passband of the filter moves from 1531.9nm to 1529.1nm.[4] It costs several seconds until spectrum of the filter becomes stable. However, the peak value and the shape of the pass band are unchanged. It means the Y field of the PVE is not changed. This suggest that no Y direction field is induced when a non-polarized light propagates in Z direction.

We also demonstrated a tunable single-wavelength filter filter realized in the PPLN by applying a temperature distribution along the sample, and observed the dependence between the wavelength shift and the temperature change of -0.598nm/^{0}C as shown in Fig.4.[5]

By a similar structure, a tunable multi-wavelength filter can also be realized. And this kind of filter is tunable in a wavelength range only limited by the temperature tuning range of the temperature control device. We believe this kind of

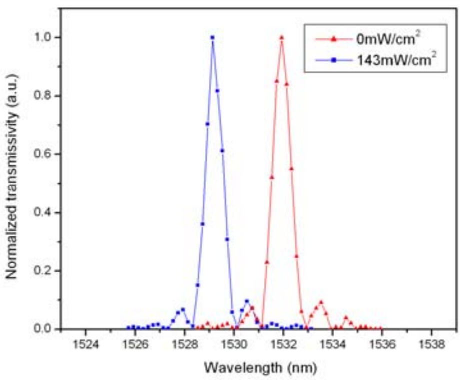

Fig. 3 The spectrum of the PPLN filter with and without UV light uniform illumination

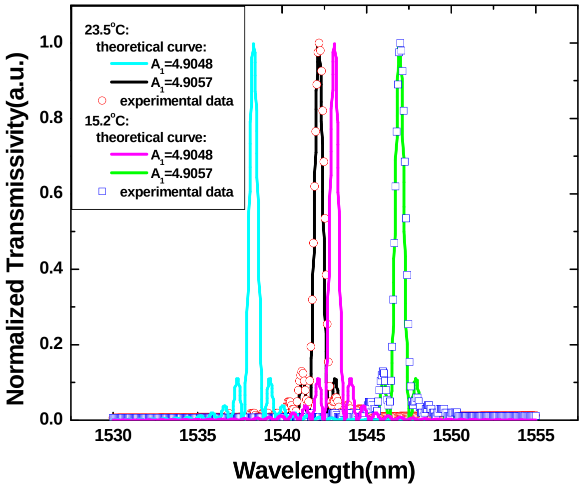

Fig.4 Tunable single-wavelength filter realized in PPLN by setting the two Peltier devices at the same temperature

multi-wavelength filter tuned by temperature will have potential applications in the dense wavelength division multiplexer (DWDM) optical fiber communication system where it can be employed for all-optical wavelength routing. Fig.5 shows tunable two-wavelength filter realized in PPLN by setting the two Peltier devices at the different temperature.[5]

3. Flexible wavelength converter

3.1 Background

Wavelength conversion through QPM difference -frequency generation (DFG) has been realized in periodically poled lithium niobate (PPLN) waveguide. DFG-based converter shows high conversion efficiency, but is complicated in mode matching of signal light (1.5-μm-band) and pump light (0.77-μm-band). For mitigating the mode matching complication, wavelength conversion based on cascaded $\chi^{(2)}$ process involving second-harmonic generation (SHG) and

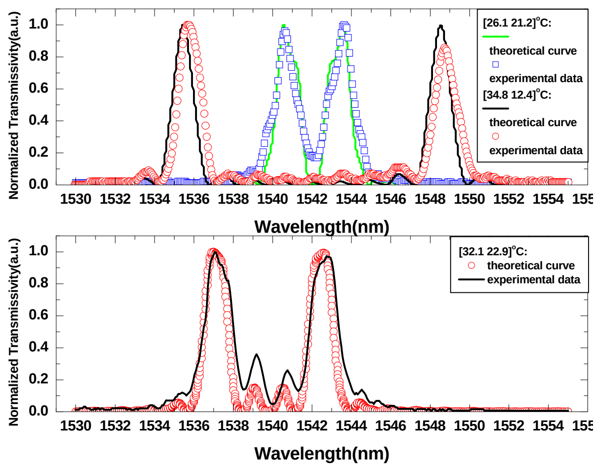

Fig. 5 Tunable double-wavelength filter realized in PPLN by applying a two-section pattern temperature distribution along the sample.

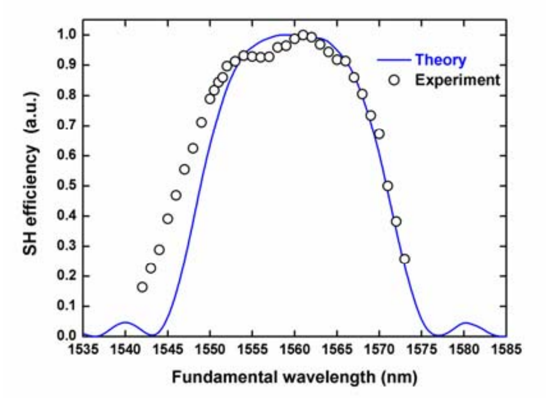

Fig.6. SHG wavelength tuning curve for PPMgLN with a 20.4 μm grating period.

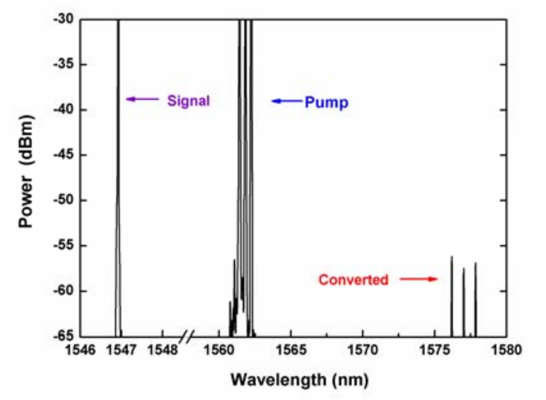

Fig.7. Measured wavelength conversion with pump tuning. The signal wavelength is fixed at 1546.92 nm.

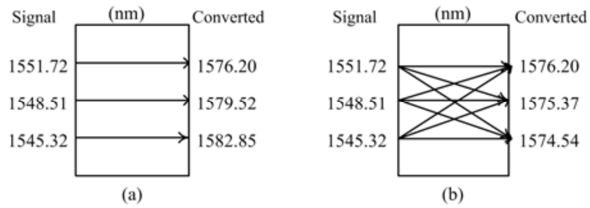

Fig.8 Limited wavelength conversion by narrow pump band versus arbitrary wavelength conversion by broad pump band.

DFG (cSHG/DFG) or cascaded sum- and difference frequency (cSFG/DFG) was proposed and demonstrated. In this scheme, the pump band is narrow and therefore signals can only be switched to limited wavelengths, resulting in poor tunability of the converter. To pursue highly tunable and flexible wavelength converter, broad and continuous pump band is desired to ensure that pump wavelength can be freely and widely set.

3.2 Devices of flexible wavelength converter

A Z-cut 5-mol. % MgO-doped PPMgLN for the wavelength converter was fabricated by the electrical poling method. The QPM grating period is 20.4μm, which enables the device to perform 1.5-μm-band wavelength conversion. Using type I interaction, a broadband SHG can be realized in this device due to satisfying QPM and group velocity matching (GVM) condition at proper wavelength and temperature. The dimension of this device is 20mm×10mm×0.5mm. By carefully tuning the pump wavelength and temperature, we obtain broadband SHG as plotted in Fig. 6. The peak normalized SH efficiency is 0.1%/W when the pump wavelength is 1562 nm at 38 ℃. The full width at half maximum (FWHM) of SH efficiency, namely SH bandwidth, is about 25nm for the 20-mm-long PPMgLN. This broad SH bandwidth can be used for widely and freely tuning pump wavelength to realize arbitrary tunable wavelength conversion, as well as for simultaneously using multiple pumps to perform broadcast wavelength conversion.

In the experiment, two tunable lasers are acted as the pump and signal source, respectively. Both the pump and signal light are mixed by a 90:10 coupler and then boosted by an erbium-doped fiber amplifier (EDFA). A lens is used to focus the lights into PPMgLN sample. The temperature of PPMgLN is controlled by a temperature controller with an accuracy of 0.1 ℃. The output light from the converter is observed by an optical spectrum analyzer (OSA). Since we use type I SHG, two polarization controllers (PC) are implemented to control the polarization of pump and signal light as ordinary light for Z-cut PPMgLN. No output SH light was observed when the pump and signal are extraordinary lights.

In the experiment, the signal wavelength is fixed at 1546.92 nm. The pump wavelength is tuned to 1561.42 nm, 1561.83 nm, 1562.23 nm, and the correspondingly converted lights are at the wavelengths of 1576.20 nm, 1577.03 nm and 1577.86 nm, respectively. The three pump wavelengths are selected according to International Telecommunication Union (ITU) grid with 50GHz spacing to obtain three converted lights with 100 GHz spacing. Fig. 7 is the combination of the three individual optical spectrums. Due to the wide tunability of pump wavelength of our scheme, the signal bandwidth of wavelength conversion is expected to be broader than other schemes. Moreover, this scheme also provides more flexible wavelength conversion solution than conventional approaches.[6)]

We further demonstrate a 3×3 arbitrary wavelength conversion using the wide tuning of pump wavelength, in which 9 pumps are used. Fig.8 illustrates the experiment results. Limited wavelength conversion using narrow pump band is compared with arbitrary wavelength conversion using broad pump band. In Fig.8 (a), the input signal (1545.32 nm, 1548.51 nm and 1551.72 nm) can only be converted to another fixed corresponding wavelength (1582.85 nm, 1579.52 nm and 1576.20 nm) by a single pump (1563.86 nm). While in Fig.8 (b), each of three input signals with 400 GHz spacing (1545.32 nm, 1548.51 nm and 1551.72 nm) is converted to any channel of the three output wavelengths with 100 GHz spacing (1574.54 nm, 1575.37 nm and 1576.20 nm). Hence, a 3×3 arbitrary wavelength conversion is realized by using 9 pumps at the wavelengths of 1559.79nm, 1560.20 nm, 1560.61 nm, 1561.42 nm, 1561.83 nm, 1562.23 nm, 1563.05 nm, 1563.45 nm and

1563.86 nm. It is noticed that a pump wavelength tuning range of 4.07 nm in broad SH bandwidth is employed for the 3×3 arbitrary wavelength conversion. A wider pump tuning range within the 25 nm SH bandwidth can be expected by selecting other input and output wavelengths.

Acknowledgement

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