The application of PPLN sum frequency generation in mid-infrared detection

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Abstract: Based on the large nonlinear coefficient of periodically poled LiNbO₃, the mid-infrared radiations can be efficiently converted into visible/near-infrared photons for sensitive detection. The up-conversion efficiency, acceptance bandwidth and the optimal pump wavelength are investigated.

1. Introduction

The mid-infrared photo detection has a host of applications in the space science, atmospheric study, pollution surveillance, military, and medical science. The mid-infrared wavelength between 3.0 μm and 4.2 μm offers intrinsic advantages in the remote sensing and lidar operations, mainly due to the eye safety, the highest atmospheric transmission, and the lowest background noise from the earth's radiations and the reflected solar radiations. Unfortunately, sensitive mid-infrared photodetectors such as InSb are only able to operate at the cryogenic ambience (liquid nitrogen 77K, liquid hydrogen 28K, liquid helium 4.2K). It is impossible for mid-infrared photo detectors to have high detectivity (D^*) and operate in the room temperature (300K) due to the background-limited condition of mid-infrared photodetectors [1]. In contrast, the visible/near-infrared photodetector like silicon avalanche photo detector (Si-APD) and single photon counting module can operate at room temperature with very high detectivity. By using nonlinear frequency up-conversion, the mid-infrared radiations can be converted into visible/near-infrared signals, and then detected by the sensitive photo detectors [2-3]. Therefore it is possible that the equivalent detectivity of mid-infrared signal is beyond the Background Limited Infrared Photon detector (BLIP). Based on the large nonlinear coefficient and no walk off of periodically poled lithium niobate (PPLN), the conversion of the 3.0-4.2 μm mid-infrared radiations into the visible/near-infrared signals is studied. In particular, the acceptance angle and the conversion efficiency are analyzed.

2. The acceptance bandwidth

The quasi-phase matching conditions of PPLN SFG can be written as

$$\frac{1}{\lambda_{sum}} = \frac{1}{\lambda_{laser}} + \frac{1}{\lambda_{mid}}, \quad (1)$$

$$\frac{n_e(\lambda_{sum})}{\lambda_{sum}} - \frac{n_e(\lambda_{laser})}{\lambda_{laser}} - \frac{n_e(\lambda_{mid})}{\lambda_{mid}} = \frac{1}{\Lambda}, \quad (2)$$

where λ_{sum} , λ_{laser} , and λ_{mid} represent the sum-frequency, pump and mid-infrared wavelengths, respectively, n_e is the extraordinary refractive index of LiNbO₃, and Λ is the period of PPLN. When the following conditions are satisfied, the maximum acceptance bandwidth can be derived,

$$\Delta\left(\frac{1}{\lambda_{sum}}\right) = \Delta\left(\frac{1}{\lambda_{mid}}\right), \quad (3)$$

$$\Delta\left(\frac{n_e(\lambda_{sum})}{\lambda_{sum}}\right) = \Delta\left(\frac{n_e(\lambda_{mid})}{\lambda_{mid}}\right). \quad (4)$$

The optimal pump wavelength (λ_{laser}^o) and the period of PPLN (Λ) can be determined when the mid-infrared wavelength (λ_{mid}) and the sum-frequency wavelength (λ_{sum}) satisfied Eqs. (3) and (4). By solving the following equations, the acceptance bandwidth can be known,

$$\frac{1}{\lambda_{sum}} = \frac{1}{\lambda_{laser}^o} + \frac{1}{\lambda_{mid}}, \quad (5)$$

$$2\pi\left(\frac{n_e(\lambda_{sum})}{\lambda_{sum}} - \frac{n_e(\lambda_{laser}^o)}{\lambda_{laser}^o} - \frac{n_e(\lambda_{mid})}{\lambda_{mid}}\right) = \frac{2\pi}{\Lambda} \pm \frac{\pi}{2l}. \quad (6)$$

Fig.1 The maximum mid-infrared acceptance bandwidth and the optimal pump wavelength via PPLN period.

Fig.2 The acceptance bandwidth of Nd:YAG laser pumped PPLN SFG via mid-infrared wavelength.

There is an optimal pump wavelength for the certain period of PPLN to obtain maximum mid-infrared acceptance bandwidth. Fig.1 shows the maximum acceptance bandwidth ($\sim 130\text{nm}$) of 25mm PPLN at the temperature of 165°C . Usually, the maximum mid-infrared acceptance bandwidth corresponds to the maximum period of PPLN controlled by quasi-phase matching conditions. For a Nd:YAG laser pumped PPLN up-conversion system, the maximum period of PPLN is $22.56\text{ }\mu\text{m}$ at the temperature of 165°C , as show in Fig.2. If the period of PPLN is shorter than the maximum value, the PPLN SFG has two separate acceptance bandwidths. For instance, if the period of PPLN is $22\text{ }\mu\text{m}$, $3.52\text{ }\mu\text{m}$ and $5.01\text{ }\mu\text{m}$ mid-infrared radiations can be simultaneously converted into the corresponding visible/near-infrared signals.

3. Up-conversion efficiency

Under the plane-wave undepleted pump approximation, the optimal pump intensity

associated with the PPLN length is expressed by the following equation,

$$I_{laser}^o = \frac{\pi^2 c \epsilon_0 \lambda_{mid} \lambda_{sum} n_e(\lambda_{mid}) n_e(\lambda_{laser}) n_e(\lambda_{sum})}{128 d_{eff}^2 L^2}. \quad (7)$$

The photon conversion efficiency of PPLN SFG is

$$\eta_{photon} = \frac{\lambda_{sum} I_{sum}(L)}{\lambda_{mid} I_{mid}(0)} \quad (8)$$

$$= \sin^2 \left(4 d_{eff} L \sqrt{\frac{2 I_{laser}}{c \epsilon_0 \lambda_{mid} \lambda_{sum} n_e(\lambda_{mid}) n_e(\lambda_{laser}) n_e(\lambda_{sum})}} \right).$$

Fig.3 The photon conversion efficiency versus the length of PPLN for various pump intensity of a $1.064\text{ }\mu\text{m}$ Nd:YAG laser, where $d_{eff} = d_{33}(1.064\text{ }\mu\text{m}) = -33 \times 10^{-12} \text{ m/V}$. For a 25 mm length PPLN crystal and 1 MW/cm^2 pump intensity of $1.064\text{ }\mu\text{m}$ laser, the calculated up-conversion efficiency is 100%.

4. Conclusion

We have investigated the sum frequency generation in the PPLN crystal to convert the mid-infrared photons into visible/near infrared for sensitive detection. It shows if the pump density is larger than 1 MW/cm^2 , the conversion efficiency can reach 100%. The acceptance bandwidth depends on the choice of pump wavelength and crystal length. At the selected pump wavelength, the bandwidth could be as wide as 130nm .

References:

- [1] E. L. Dereniak, and D. G. Crowe, *Optical Radiation Detectors* (John Wiley & Sons, New York, 1984), Chap. 4
- [2] J. Warner, "Difference Frequency Generation and Up-conversion," in *Quantum Electronics*, H. Rabin and C. L. Tang, ed (Academic Press, New York, 1975).
- [3] M. A. Albota, and N. C. Wong, "Efficient single-photon counting at $1.55\text{ }\mu\text{m}$ via frequency upconversion," CLEO/QELS, QThPDB11, Baltimore, Maryland USA (2003), pp.1-3.