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

Yingxin Bai1, Jirong Yu2, N. P. Barne2, Songsheng Chen1, Mulugeta Petros3, H. R. Lee4, B. C. Trieu2, U. N. Singh2

1Science Applications International Corporation, One Enterprise Parkway, Suite 300, Hampton, VA 23666-5845
yingxin_bai@yahoo.com
2NASA Langley Research Center, MS. 468, Hampton, VA 23681
3Science and Technology Corporation, 101 Research Drive, Hampton, VA 23666
4Department of Physics, Hampton University, VA 23668

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 upconversion 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 3.0-4.2μm 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

\[
\frac{1}{\lambda_{\text{sum}}} = \frac{1}{\lambda_{\text{laser}}} + \frac{1}{\lambda_{\text{mid}}},
\]

(1)

\[
\frac{n_e (\lambda_{\text{sum}})}{\lambda_{\text{sum}}} - \frac{n_e (\lambda_{\text{laser}})}{\lambda_{\text{laser}}} - \frac{n_e (\lambda_{\text{mid}})}{\lambda_{\text{mid}}} = \frac{1}{\Lambda},
\]

(2)

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

\[
\Delta \left( \frac{1}{\lambda_{\text{sum}}} \right) = \Delta \left( \frac{1}{\lambda_{\text{mid}}} \right),
\]

(3)

\[
\Delta \left( \frac{n_e (\lambda_{\text{sum}})}{\lambda_{\text{sum}}} \right) = \Delta \left( \frac{n_e (\lambda_{\text{mid}})}{\lambda_{\text{mid}}} \right).
\]

(4)

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

\[
\frac{1}{\lambda_{\text{sum}}} = \frac{1}{\lambda_{\text{laser}}^{o}} + \frac{1}{\lambda_{\text{mid}}},
\]

(5)

\[
2\pi \left( \frac{n_e (\lambda_{\text{sum}})}{\lambda_{\text{sum}}} - \frac{n_e (\lambda_{\text{laser}}^{o})}{\lambda_{\text{laser}}^{o}} - \frac{n_e (\lambda_{\text{mid}})}{\lambda_{\text{mid}}} \right) = \frac{2\pi}{\Lambda} \pm \frac{\pi}{2l}.
\]

(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 (~130nm) 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 μm 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 μm, 3.52 μm and 5.01 μm 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,

\[ P_{\text{opt}} = \frac{\pi^2 c e_{\text{nl}}^2 (\lambda_{\text{mid}} n_2 (\lambda_{\text{mid}}) n_2 (\lambda_{\text{mid}}))}{128 d_{\text{eff}} L^2} \]  

The photon conversion efficiency of PPLN SFG is

\[ \eta_{\text{photon}} = \frac{\lambda_{\text{mid}}}{\lambda_{\text{mid}} + \lambda_{\text{sum}}} \]  

\[ \eta_{\text{photon}} = \sin^2 \left( \frac{2I_{\text{laser}}}{4d_{\text{eff}} L} \right) \]  

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 1MW/cm², 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: