Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 6-3, Ajaccio, Corsica, France, October 9-12 (2012)

Progress on non-linear SFG use for high resolution imaging

Jean-Thomas Gomes
Ludovic Grossard
Damien Ceus
Laurent Delage
and François Reynaud
Xlim, Département Photonique
Université de Limoges UMR CNRS 6172
123 Av. Albert Thomas
87060 Limoges CEDEX, France
Email:jean-thomas.gomes@unilim.fr

Sébastien Vergnole
Horiba Scientific
231 rue de Lille
59650 Villeneuve d'Ascq, France

Harald Herrman
and Wolfgang Sohler
Universität Paderborn
Angewandte Physik
Warburger Str.
100-33098 PADERBORN, Germany

***Abstract*—For more than ten years we intend to promote the use of nonlinear optics in the frame of high angular resolution imaging for astronomy. The shift of the optical spectrum by nonlinear effects allows to overcome many difficulties resulting from the processing and detection of an infrared light. This paper reports on the experimental implementation of a sum frequency generation process (SFG) powered by a pump spectral doublet. The aim of this configuration is to allow the use of the SFG process over an enlarged spectral domain. By analyzing the converted signal, we numerically and experimentally demonstrate a frequency spectral compression effect from the infrared input signal to the visible one converted through the SFG process. The experimental setup, based on an up-conversion interferometer, permits to demonstrate an experimental frequency spectral compression factor of 3.56. This study takes place in the general field of coherence analysis through second order non-linear processes.**

I. Introduction

High resolution stellar interferometers are very powerful instruments to get a better knowledge of our Universe through the spatial coherence analysis of the light. This analyze is classically achieved by mixing the optical fields collected by a set of telescopes T_i of the stellar interferometer. These interferometric patterns provide two different informations called the contrast C_{ij} and the phase φ_{ij}, which compose the complex visibility $V_{ij} = C_{ij} exp(j\varphi_{ij})$.

In the astronomical domain, it is very interesting to achieve the coherence analysis of a signal at mid- and far- infrared wavelengths. Currently, the optical technologies available at these wavelengths suffer from lots of technical difficulties (components transmission, thermal noise, thermal cooling, ...), which leads to hard restrictions about the imaging of astronomical sources in these wavelength domains.

As mature optical technologies are available for light transport and detection at visible or near infrared wavelengths, our team promotes an original approach in order to find a solution to the limitation of infrared optics. Instead of developing new infrared technologies, we propose to use non-linear optical techniques to shift the infrared radiation of an astronomical source into visible wavelengths in order to perform the light processing. In our case, we use sum frequency generation process (SFG), in periodically poled Lithium Niobate (PPLN) waveguides, to convert a 1550 nm infrared wave to a 630 nm visible wave by using a pump source.

This way, we implemented a SFG process on each arm of a classical interferometer in order to analyse the complex visibility of an infrared source operating at visible wavelenghts. With this kind of device, called SFG interferometer, we already demonstrated the ability to analyze the coherence properties of an infrared signal through an up-conversion process in a two and a three-arm interferometer without information loss [1], [2].

All over these first experiments, we were limited by the spectral acceptance of the PPLN waveguides. With a single line pump, only a narrow spectral bandwidth of the IR source spectrum is converted because of the limited spectral acceptance of the PPLN.

To overcome this spectral limitation, we intend as long term goal, to study a SFG process powered by a pump frequency comb. This method is dedicated to increase the spectral bandwidth to be analyzed through an up-conversion process.

We report here the first step of our work, consisting in the coherence analysis of an infrared spectral doublet through the SFG inteferometer powered by a pump spectral doublet. We highlight here that the use of a pump frequency comb to power a SFG process could lead to a frequency spectral compression effect between the input and the output of the up-conversion process.

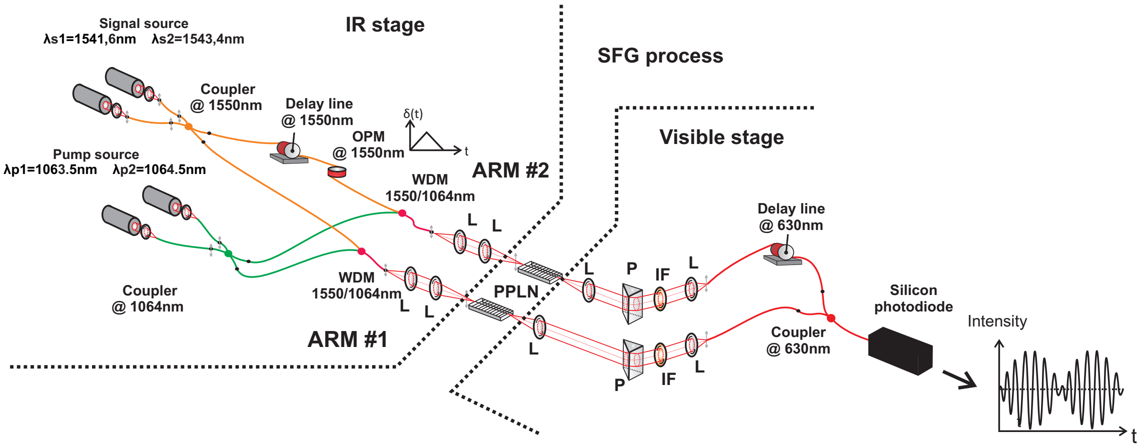

Fig. 1. Experimental setup of the SFG interferometer. OPM: optical path modulator, WDM: wavelength division multiplexer, L: lens, P: prism, IF: interference filter

II. Experimental setup and theoretical expression of the fringe pattern

A. Experimental setup

Our setup is based on a Mach-Zehnder interferometer as shown in Fig.1. This interferometer is fed by an input signal composed of a set of two distributed-feedback (DFB) lasers ($\lambda_{s1} = 1541.9$ nm, $\lambda_{s2} = 1543.6$ nm) and two laser pump sources ($\lambda_{p1} = 1063.5$ nm and $\lambda_{p2} = 1064.5$ nm). The DFB signals are mixed together and equally shared to the two interferometric arms by a fiber coupler. The pump sources are also mixed and equally shared by a 1064 nm single-mode coupler. A 10-cm stroke fibered delay line is inserted in the arm #2 to adjust the OPD between the two arms in the infrared stage of the interferometer. An optical path modulator (OPM), with a 100-μm stroke, is inserted in the same arm for a fine OPD adjustment and to induce a temporal optical path modulation on the input signal. This allows to display the fringe pattern as a function of time. This device is driven by a triangular high voltage to induce a linear OPD as a function of time.

The DFB and pump sources are spectrally multiplexed thanks to a fibered wavelength division multiplexer (WDM) before the SFG stage on each arm of the interferometer. In each arm, the emerging multiplexed beams are focused by achromatic injection systems in a Ti-indiffused type I 4 cm long PPLN waveguide with a spectral acceptance of 0.3 nm at 1550 nm. These non linear crystals are placed in thermally regulated enclosures to control a proper phase matching of the expected SFG process. The emerging up-converted signals at 630 nm are spectrally selected on each arm by a spectral filtering stage, composed of a dispersive prisms (P) and an interference filter (IF) centered on the mean converted wavelength. After this stage, our converted signals are spatially filtered thanks to the use of single-mode polarization maintaining fiber at the converted wavelength. We have inserted another fiber delay line on arm #2, with 10-cm stroke, to control the OPD between the two arms of the interferometer on the visible path. At the output of the parametric interferometer, we combine the two visible optical fields by using a polarization maintaining and single-mode fiber coupler. The resulting fringe pattern is then detected by a Silicon photodiode.

B. Theoretical expression of the fringe pattern at the output of the SFG interferometer

In this part, we derive the contrast expression at the output of the interferometer. This expression allows us to analyze the coherence properties of the input spectral doublet.

At the output of the SFG interferometer, we can write the fringe pattern expression for each line of the input spectral doublet λ_{s1} and λ_{s2} as:

$$Itot_{s1} \propto 1 + \cos(\Delta\varphi_{s1} + \Delta\varphi_{c1}) \quad (1)$$

$$Itot_{s2} \propto 1 + \cos(\Delta\varphi_{s2} + \Delta\varphi_{c2}) \quad (2)$$

Where $\Delta\varphi_{s1}$ and $\Delta\varphi_{s2}$ are the phase difference expressions on the infrared stage between the two arms of the interferometer for each peak of the input spectral doublet λ_{s1} and λ_{s2}. $\Delta\varphi_{c1}$ and $\Delta\varphi_{c2}$ are the phase difference expressions on the visible stage between the two arms of the interferometer for each peak of the converted spectral doublet λ_{c1} and λ_{c2}.

The resulting interferometric signal at the output of our interferometer is equal to the sum of the intensities of these two fringe systems. The mathematical expression of this signal $Itot$ contains an envelop term modulating our interference pattern. In the following, we will focus our study on this envelop term.

$$Itot = Itot_1 + Itot_2 \quad (3)$$

$$Itot \propto 1 + \text{envelop} \times \text{fringes} \quad (4)$$

$$envelop = \cos\left[\frac{\pi \cdot \Delta\delta_{IR} \cdot \Delta\lambda_s}{\overline{\lambda_s}^2} + \frac{\pi \cdot \Delta\delta_{Vi} \cdot \Delta\lambda_c}{\overline{\lambda_c}^2}\right] \quad (5)$$

where $\overline{\lambda_c} \approx (\lambda_{c1} + \lambda_{c2})/2$, $\overline{\lambda_s} \approx (\lambda_{s1} + \lambda_{s2})/2$, $\Delta\lambda_s = \lambda_{s2} - \lambda_{s1}$ and $\Delta\lambda_c = \lambda_{c2} - \lambda_{c1}$. The contrast evolution of the fringe pattern is driven by the two different spectral separations related to the signal and the converted waves. When applying an OPD between the two interferometric arms on the infrared stage, the envelop period depends on the spectral separation of the input signal ($\Delta\lambda_s$). Conversely, when applying an OPD on the visible stage, the envelop period depends on the spectral separation of the converted signal ($\Delta\lambda_c$).

So, due to the relationship between the contrast evolution and the frequency spectral separation between the two lines of the infrared and converted signal, we have to check that the SFG process powered by a pump spectral doublet does not change the coherence informations contain in the input signal.

III. Results and Discussion

A. Experimental results

In a previous work, we have demonstrated the temporal coherence conservation of a infrared signal composed by spectral doublet through a SFG interferometer using up-conversion processes powered by a single line pump [3].

In order to be sure that the use of a pump spectral doublet does not change the temporal coherence properties of the infrared input signal after the SFG process, we conducted two different measurements of the contrast evolution as a function of the OPD between the two arms of the interferometer: the first one by applying this OPD on the infrared path, the second one by applying the OPD on the visible stage.

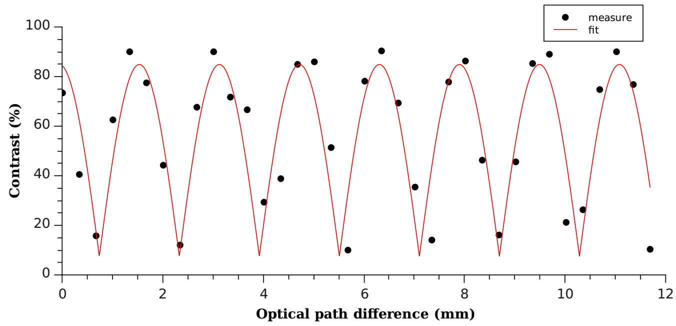

Fig. 2. Experimental fringe contrast versus the OPD at infrared wavelengths. Dots represent the measured contrast. The red curve is the best theoretical fit. The beat length, which is equal to the contrast period, is $L_{bIR} = 1.59$ mm

Fig.2 shows the experimental fringe contrast versus the OPD at infrared wavelengths. The beat length of the fringe pattern envelop is equal to $L_{bIR} = 1.59$ mm. When the OPD is modulated on the visible stage (Fig.3), the beat length L_{bVi} is equal to 5.66 mm. The periodicity difference between these contrast curves experimentally demonstrates a frequency spectral compression effect resulting from a multipump configuration in a sum frequency generation process. The experimental frequency spectral compression factor ρ_{exp} is equal to:

$$\rho_{exp} = \frac{L_{bVi}}{L_{bIR}} = 3.56 \quad (6)$$

B. Simulation results

The frequency spectral compression effect has been numerically studied. We have computed a SFG process corresponding to our experimental setup (PPLN properties, pump source

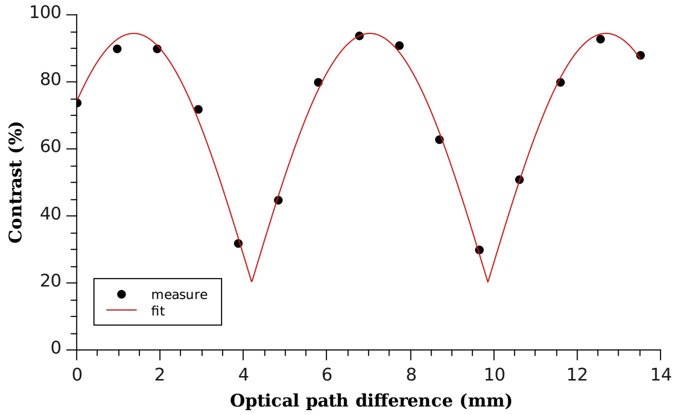

Fig. 3. Experimental fringe contrast versus the OPD at converted wavelengths. Dots represent the measured contrast. The red curve is the best theoretical fit. The beat length, which is equal to the contrast period, is $L_{bVi} = 5.66$ mm

spectrum, ...). This simulation computes the converted signal intensity spectrum at the output of the SFG process and permits us to estimate the frequency spectral compression factor between the infrared input signal and the converted signal.

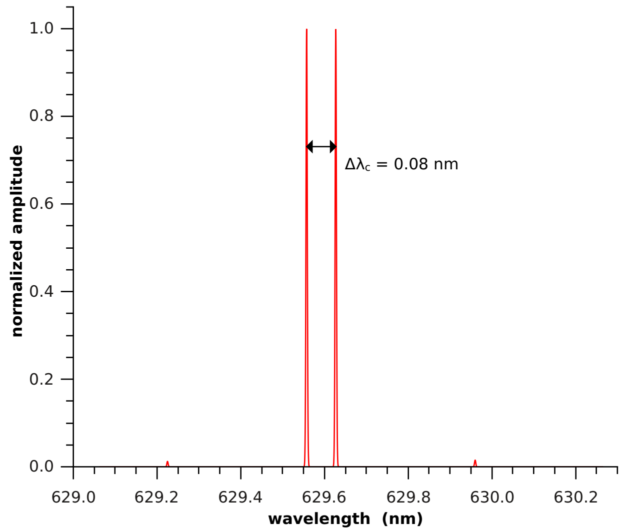

Fig. 4. Normalized spectrum of the converted signals. λ_{c1} and λ_{c2} are the two main converted peak wavelengths

Fig. 4 shows the normalized converted intensity spectrum of an infrared spectral doublet converted through the SFG process powered by a pump spectral doublet using our experimental setup values ($\lambda_{s1} = 1541.9$ nm, $\lambda_{s2} = 1543.6$ nm). Through the SFG process powered by a single line pump, the separation between the two converted peaks $\Delta\lambda_c$ would be equal to 0.62 nm without any frequency compression. In our case, we obtain two converted peaks around 629.5 nm separated by $\Delta\lambda_c = 0.08$ nm.

As the spectral separation before SFG process is $\Delta\lambda_s =$

1.7 nm, we have calculated the theoretical frequency spectral compression factor:

$$\rho_{th} = \frac{\Delta\nu_s}{\Delta\nu_c} = \frac{\Delta\lambda_s}{\Delta\lambda_c} \cdot \frac{\overline{\lambda_c}^2}{\overline{\lambda_s}^2} = 3.54 \qquad (7)$$

where $\overline{\lambda_c} \approx (\lambda_{c1} + \lambda_{c2})/2$ and $\overline{\lambda_s} \approx (\lambda_{s1} + \lambda_{s2})/2$.

This result is in a very good agreement with the experimental results ($\rho_{exp} = 3.56$) reported above (relative difference lower than 0.6%) and shows that our analysis is valid.

C. Discussion

Such a frequency spectral compression could be used to reduce the impact of the fiber chromatic dispersion effects for a fibered interferometer dedicated to coherence analysis. For example, a source centered at 1550 nm with 20 nm spectral bandwidth propagating in a 20 ps/(nm.km) optical fiber suffers from a chromatic dispersion of 400 ps/km. The corresponding converted signal through a SFG process powered by an optimized pump frequency comb is centered on 630 nm with a 0.94 nm spectral bandwidth. This radiation propagating in a 200 ps/(nm.km) single-mode fiber suffers from a chromatic dispersion of only 140 ps/km due to the frequency spectral compression.

IV. Conclusion

In this paper, we have presented the implementation of an up-conversion interferometer powered by a pump spectral doublet. Through this experiment, we have demonstrated the frequency spectral compression effect of an infrared signal through the SFG process. This setup has provided experimental results with a high reliability (relative difference between numerical and experimental results lower than 0.6%).

Frequency spectral compression effect will permit to relax the constraint on the optical path equalization in a fibered interferometer, allowing an easier implementation while analyzing a broadband source.

The next step of our experimental study will be dedicated to increase the spectral bandwidth to be analyzed through an up-conversion process. This way, we will implement a pump frequency comb to analyze the coherence of large spectral bandwidth infrared sources using the SFG process. Thus, we will propose an alternative method for high resolution imaging using non-linear optics combined with spatial coherence analysis [1], [2].

Acknowledgment

This work has been financially supported by the Centre National d'Études Spatiales (CNES) and by the Institut National des Sciences de l'Univers (INSU). Our thanks go to A. Dexet for the development and his advices for all the specific mechanical components.

References

[1] S. Brustlein, L. Del Rio, A. Tonello, L. Delage, F. Reynaud, H. Herrmann, W. Sohler, Laboratory demonstration of an infrared-to-visible up-conversion interferometer for spatial coherence analysis, Phys. Rev. Lett. 100 153903 (2008) 153903.

[2] D. Ceus, A. Tonello, L. Grossard, L. Delage, F. Reynaud, H. Herrmann, W. Sohler, Phase closure retrieval in an infrared-to-visible upconversion interferometer for high resolution astronomical imaging, Opt. Lett. 19 (2011) 8616–8624.

[3] L. Del Rio, M. Ribiere, L. Delage, F. Reynaud, First demonstration of a temporal coherence analysis through a parametric interferometer, Opt. Commun. 281 (2008) 2722–2726.