Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **427,** L95–L98 (2012) doi:10.1111/j.1745-3933.2012.01352.x

Application of frequency conversion of starlight to high-resolution imaging interferometry. On-sky sensitivity test of a single arm of the interferometer

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Accepted 2012 September 13. Received 2012 September 11; in original form 2012 July 6

ABSTRACT

We investigate the sensitivity of frequency conversion of starlight using a non-linear optical sum frequency process. This study is being carried out in the context of future applications of optical interferometry dedicated to high-resolution imaging. We have implemented a complete experimental chain from telescope to detector. The starlight frequency is shifted from the infrared to the visible using an optically non-linear crystal. To fulfil the requirements of interferometry, our experimental setup uses spatially single-mode and polarization maintaining components. Due to the small size of the collecting aperture (8 inches Celestron C8) with a 3 nm spectral bandwidth, on-sky tests were performed on bright stars in the *H* band. The detection was achieved in a true photon counting operation, using synchronous detection. Betelgeuse (HMag = −3.9), Antares (HMag = −3.6) and Pollux (HMag = −1) were successfully converted and detected in visible light. Despite the low transmission of our experiment, our results prove that the efficiency of frequency conversion offers sufficient sensitivity for future interferometric applications.

Key words: instrumentation: miscellaneous – instrumentation: photometers – methods: observational – techniques: interferometric.

1 INTRODUCTION

Our knowledge of astronomical sources is mainly brought to us by the electromagnetic waves emitted from the X-rays to the radio waves. To investigate such an ultrawide wavelength domain, a large variety of instruments have been designed and implemented. Even in the limited optical domain spectrum, the usual way to propose an instrumental concept is to develop an experimental chain (including the collecting antenna, wave propagation, optical processing and detection) specifically dedicated to the narrow spectral window to be investigated. It can be very stringent to design and manufacture the related optical components with convenient optical characteristics. Conversely, we propose to use an instrumental chain working in a technologically mature wavelength domain and to shift the astronomical spectrum into this spectral domain. There are several advantages to using such a frequency conversion, especially from far-mid-infrared to near-infrared or visible wavelengths: the possibility of using spatially single-mode and polarization maintaining components which are easy to handle and have low optical losses (optical fibres and integrated optical combiners), the availability of efficient detectors (high quantum efficiency, low noise, room temperature operation) and not to be compelled to use complex cooling systems over the entire instrument (assuming the frequency conversion takes place right after the telescope focus).

Previous results (Gurski 1973) have reported astronomical image conversions during the 1970s to 1980s. If this concept appeared to be very attractive to astronomers, the frequency conversion process was limited by a poor conversion efficiency and an unknown noise was observed (Boyd 1977). Recent studies and technological developments have significantly enhanced the quality and the efficiency of the related non-linear components (Kamada et al. 2008; Thew, Zbinden & Gisin 2008). Thanks to these improvements, we intend to develop a new kind of interferometer using the non-linear techniques associated with a telescope array such as, for example, the VLTI or CHARA. In this coherence

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analysis context, reliable observables are achievable only if the optical propagation of light is coherently managed in the interferometer (spatially single-mode and polarization maintaining propagation, etc.) (Froehly 1981; Coudé du Foresto 1997; Delage & Reynaud 2000). We have recently demonstrated, in laboratory experiments, the conservation of the spatial complex coherence of an artificial star, after frequency conversion in both arms of a fibre-linked interferometer (Brustlein et al. 2008; Ceus et al. 2011). The aim of the study reported in this Letter is to prove that astronomical light can be converted and detected with a proper sensitivity despite the tremendous dynamic range between the power of the signal to be detected and the pump laser used for the non-linear frequency conversion. Moreover, our demonstrator has to satisfy the single-mode and polarization maintaining requirements necessary for future applications to high angular resolution imaging interferometry. We have implemented a complete detection chain (from the collecting aperture to the detector) using single-mode and polarization maintaining components for the propagation of the infrared and the converted lights. The experiment has been conducted with an astronomical spectrum in the *H* band in order to take advantage of the mature technology developed around 1.5 μm for optical telecommunications.

Section 2 describes the non-linear process used to shift the astronomical spectrum. Section 3 describes our demonstrator and the related data processing. Then, the results are reported followed by a discussion and a conclusion.

2 BACKGROUND ON THE NON-LINEAR EFFECT

The following part is a brief description of the non-linear effect used in this study. More details about non-linear optics can be found in Boyd (2008). The non-linear process involved in our study is sum frequency generation (SFG) resulting from the non-linear mixing between three optical waves:

(i) the astronomical light at the wavelength λ_{AL}
(ii) the pump source at λ_{p}
(iii) the converted signal at λ_{c}

The conservation of energy over this process leads to the following equation:

$$\frac{1}{\lambda_{\mathrm{AL}}} + \frac{1}{\lambda_{\mathrm{p}}} = \frac{1}{\lambda_{\mathrm{c}}}. \tag{1}$$

In addition, the non-linear conversion efficiency is maximal when the three waves satisfy the phase matching condition. This phase condition can be expressed as a function of the wavevector of each beam and strongly depends on the optical properties of the non-linear crystal. In our study, we used a periodically poled lithium niobate (PPLN) crystal, allowing a coaxial propagation of the three interacting waves. In this case, we talk about the quasi-phase matching condition, given by

$$k_{\mathrm{AL}} + k_{\mathrm{p}} - k_{\mathrm{c}} + k_m = 0\,, \tag{2}$$

where $k_i = 2\pi n_i/\lambda_i$ (i = AL, p, c) is the wavenumber of the astronomical light, the pump source and the converted signal, respectively, and n_i is the corresponding refractive index. $k_m = 2\pi m/\Lambda$ is the magnitude of the grating vector associated with the mth Fourier component of the spatial variation of the non-linear coefficient, and Λ is the period of the ferroelectric inversion of the PPLN.

The best conversion efficiency is obtained through use of the first-order ($m = 1$) interaction. The quasi-phase matching condition then writes

$$\frac{2\pi n_{\mathrm{AL}}}{\lambda_{\mathrm{AL}}} + \frac{2\pi n_{\mathrm{p}}}{\lambda_{\mathrm{p}}} - \frac{2\pi n_{\mathrm{c}}}{\lambda_{\mathrm{c}}} + \frac{2\pi}{\Lambda} = 0. \tag{3}$$

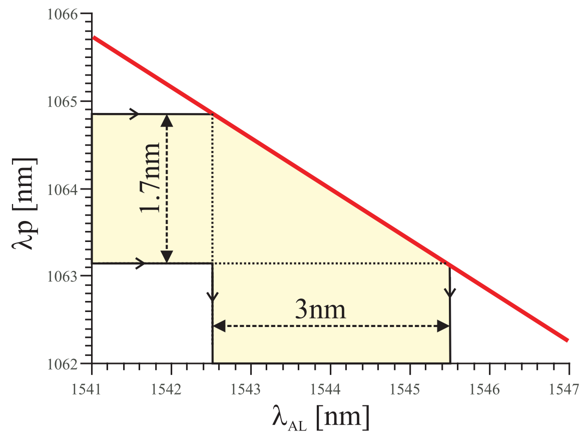

Figure 1. Spectral selectivity of the SFG process: the red curve gives the wavelength of the pump wave leading to the maximum conversion efficiency versus the astronomical wavelength to be converted according to equation (3). Using a 1.7 nm bandwidth pump laser, it is possible to convert a 3 nm spectral window in the *H* band. The wavelength of the converted signal λ_{c} is not represented here, but can be easily deduced from equation (1).

The non-linear conversion efficiency is strongly enhanced when the fields are confined into a single-mode waveguide etched on the surface of the PPLN, thus increasing the overlap integral of the beams. The waveguide is realized by diffusion of titanium.

There are two ways to select the astronomical wavelength to be converted. We can either change the wavelength of the pump source at a given temperature of the non-linear crystal, or change the temperature of the crystal at a given pump source wavelength. In our study, we used a 4-cm-long PPLN operating at 90°C. The waveguide was 6 μm wide and the period of the ferroelectric inversion was equal to $\Lambda = 10.85$ μm. With these parameters, we have numerically computed the variation of the astronomical wavelength to be converted as a function of the pump wavelength using equation (3) (see Fig. 1). The refractive indices have been computed using the temperature-dependant Sellmeier equation (Jundt 1997). This way, a 1.7-nm-wide pump spectral band centred at 1064 nm can convert a 3 nm astronomical spectral window centred at 1544 nm.

3 EXPERIMENTAL SETUP

Our experimental setup corresponds to one arm of a future upconversion interferometer operating in the *H* band (see Fig. 2) that would include a frequency conversion stage in each arm. The astronomical light input spectrum is centred at $\lambda_{\mathrm{AL}} = 1544$ nm. The pump laser spectrum is 1.7 nm wide and is centred at $\lambda_{\mathrm{p}} = 1064$ nm. According to equation (1), the converted spectrum is then centred at $\lambda_{\mathrm{c}} = 630$ nm. The astronomical light is collected by a modified amateur C8 (8 inches aperture) telescope borrowed from the OHANA-Iki project (Baril et al. 2010). The C8 telescope is used to feed a single-mode fibre. A tip-tilt mirror, placed between the optical fibre and the collecting aperture, and a camera (used to send the position offsets to the tip-tilt mirror) allow us to stabilize the focused beam on the fibre input. Thanks to the good atmospheric conditions at the Mauna Kea summit (seeing better than 0.5 arcsec during the observation nights), the tip-tilt correction is efficient enough to launch the astronomical light into a single-mode fibre.

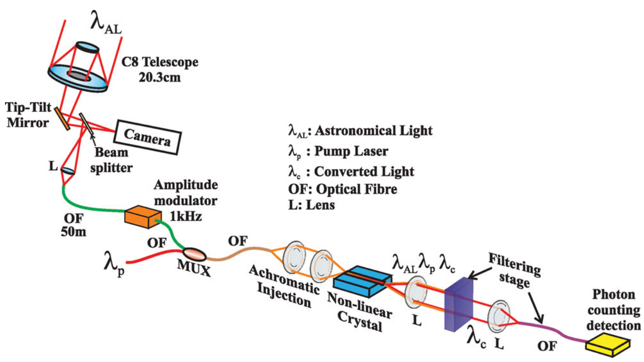

Figure 2. Astronomical light ($\lambda_{AL} = 1544$ nm) collected by the C8 telescope feeds a 50-m-long single-mode optical fibre over the *H* band. The starlight is amplitude-modulated through a lithium niobate modulator and is mixed with a pump laser (300 mW fibred pigtail laser photodiode at $\lambda_p = 1064 \pm 0.85$ nm) by means of a multiplexer. The output of the multiplexer feeds an achromatic injection device for optimized coupling to the waveguide of a non-linear PPLN crystal. At the output of the PPLN waveguide, the converted light is collimated and spectrally filtered with a prism and a narrow bandwidth filter centred on the converted wavelength. A long single-mode optical fibre at 630 nm completes the pump laser rejection and guides the converted light to a Si-APD photon counting detector.

The astronomical light is tagged through an amplitude modulation at 1 kHz, and is then synchronously detected to enhance the signal-to-noise ratio (S/N). The astronomical beam is mixed with the pump laser (300 mW) by a fibred multiplexer. The fibre output of the multiplexer is connected to a free space achromatic injection device (using off-axis parabolas and mirrors) that couples the light into the PPLN waveguide. The non-linear crystal is placed in a 90°C temperature stabilized oven used to reach the quasi-phase matching conditions for the (λ_{AL}, λ_p) wavelengths. At the output of the PPLN waveguide, a set of spatial and spectral filtering stages are used to remove the residual pump light that could disturb the photon counting detection of the converted light. In our study, the optical power ratio between the converted and the pump beams is equal to 10^{-15}. Finally, the converted light is sent to a silicon avalanche photodiode (Si-APD) detector. A photon counting event can arise from three kinds of phenomena: the converted photons due to the SFG process, the detection of the pump source or related noise and the dark counts of the avalanche photodiode. The latter is the intrinsic noise of the Si-APD photon counting detector with no light on (in our study, the dark count rate is equal to 90 counts s^{-1}).

The signal processing is based on the detection of the astronomical light modulation at 1 kHz through an averaging of the spectrum.

4 RESULTS

Fig. 3 plots the curves related to Betelgeuse (MMag − 3.9 in the *H* band with a spectral flux density of 4.7×10^{-13} W cm^{-2} µm^{-1}). For each curve we averaged the Fourier transform of the photon counting signal, then took its modulus. For Betelgeuse, we used 500 acquisition frames, with 0.1 s duration per frame. The red curve is an acquisition with simultaneously the Betelgeuse light and the pump laser. The converted signal clearly reveals the expected modulation peak at 1 kHz. The black and blue curves show acquisitions without the pump light and without the Betelgeuse light, respectively. For these two configurations, the absence of the modulation peak at 1 kHz proves that the red peak at 1 kHz is due to the frequency conversion of light and not from a spurious modulation. The S/N over 50 s (i.e. 500 frames) is equal to 17 when Betelgeuse is converted from the infrared to the visible wavelength. The S/N calculus is equal to the signal mean value over the noise mean value. Fig. 4 presents the results for two other stars: Antares (MMag = −3.6 in the *H* band, averaged over 400 frames) and Pollux (MMag = −1 in the *H* band, averaged over 6000 frames). For both of them, the star and the pump sources fed the frequency conversion bench. The 1 kHz peak is due to the frequency conversion process with a S/N equal to 19 (over 400 frames) for Antares and 3.1 (over 6000 frames) for Pollux. Notice that the S/N for Antares is higher than the Betelgeuse S/N. This could be explained by a better coupling efficiency between the C8 telescope and the single-mode optical fibre during the 40 s of average time (the seeing conditions may have changed since the measurements were made during two different nights).

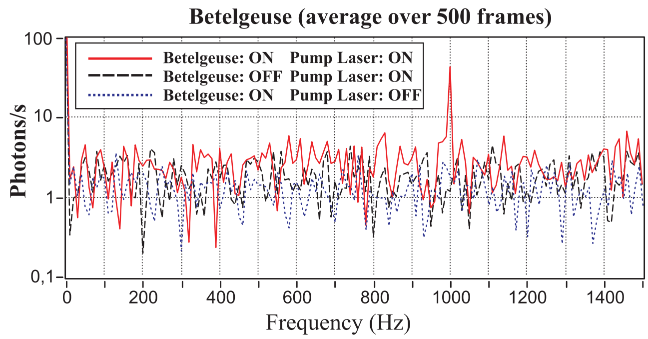

Figure 3. Frequency conversion of Betelgeuse (MMag = −3.9 in the *H* band). Red solid line: Betelgeuse and the pump source on. Black dashed line: Betelgeuse off and the pump source on. Blue dotted line: Betelgeuse on and the pump source off.

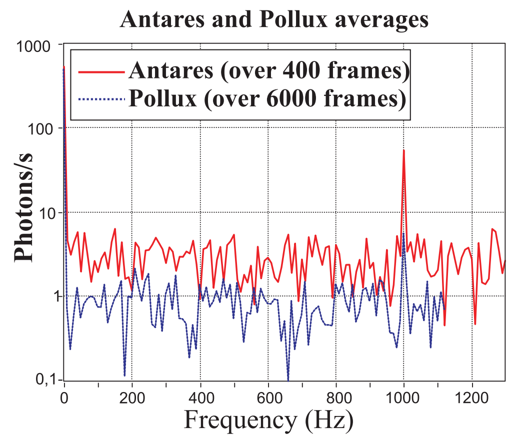

Figure 4. Frequency conversion for Antares (MMag = −3.6 in the *H* band, red solid line) and Pollux (MMag = −1 in the *H* band, blue dotted line). In both cases, the pump source and the astronomical light feed the frequency conversion bench.

Fig. 5 plots the evolution of the S/N versus the averaging time for the three converted stars. In a few seconds for Antares and Betelgeuse, the S/N is better than 2 and the evolution as a function of time follows the theoretical root mean square curve. Due to the higher magnitude of Pollux and probably the injection instabilities of the C8 telescope, the S/N for Pollux rises over the averaging time with a more disturbed evolution.

5 DISCUSSION

To complete our experimental study, we evaluated the transmission coefficients of the different stages (see Fig. 6) and made the

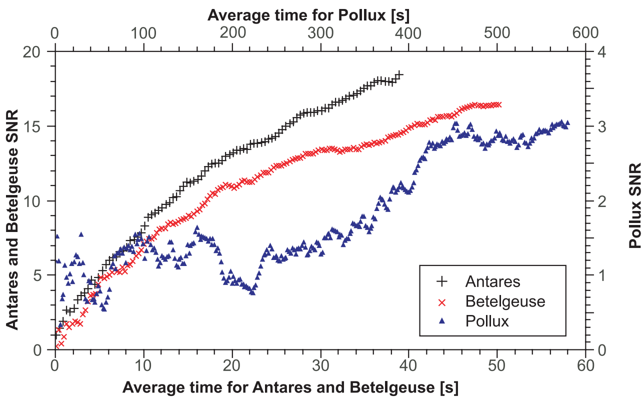

Figure 5. S/N plots for Antares, Betelgeuse and Pollux over the averaging time.

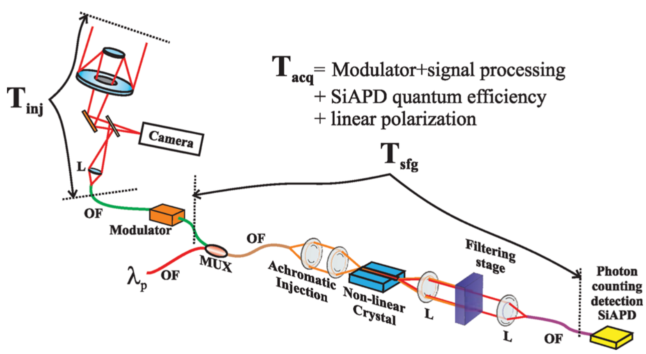

Figure 6. Parameters used to evaluate the global throughput.

energy budget of the entire instrumental chain. The instrument consists of three main optical functionalities: the telescope/single-mode waveguide coupling, the frequency conversion and the signal processing and detection. A measurement of H band flux launched in the fibre by using the CAID NICMOS camera (Baril et al. 2010) allows us to measure the throughput $T_{\rm inj}$ between the telescope and the input of the intensity modulator. Moreover, to determine the global transmission $T_{\rm sfg}$ between the input of the fibred multiplexer and the photon counting detector, we used a laser source at 1540 nm as a reference infrared signal to convert. Note that $T_{\rm sfg}$ takes the multiplexer losses, the PPLN coupling losses, the non-linear efficiency, the spectral filtering (prism and interference filter), and the spatial filtering (monomode fibre @ 630 nm) into account. Finally, $T_{\rm acq}$ gathers several parameters: the 0.5 coefficient of the Fourier transform, the Si-APD quantum efficiency (0.8), the optical loss (0.5), the duty cycle (0.5) of the amplitude modulator and the 0.5 coefficient of polarization filtering. Table 1 gives the different throughput coefficients of our experimental setup.

Table 1. Throughputs of our experimental setup.

Parameter	Value
$T_{\rm inj}$	0.0035
$T_{\rm sfg}$	0.01
$T_{\rm acq}$	0.05
Total	1.75×10^{-6}

We can notice that the major limitation of our experimental setup is currently due to the low coupling efficiency of the starlight collected by the mere C8 amateur telescope into the single-mode fibre. According to Shaklan & Roddier (1988) and Coudé du Foresto et al. (1996), we can expect to gain two orders of magnitude in $T_{\rm inj}$. Moreover, using commercially available fibre pigtailed non-linear crystals dedicated to the H band and higher laser pump powers, $T_{\rm sfg}$ could be significantly enhanced. In the view of the expectable improvement in the global transmission of this instrument chain, these first experimental results are very promising.

6 CONCLUSIONS

We successfully converted the astronomical light emitted by Betelgeuse, Antares and Pollux using a non-linear process in the experimental context required by astronomical interferometry: spatially single-mode and polarization preserving beam propagation. This way, we demonstrated on-sky that the non-linear frequency conversion has enough sensitivity to be applied to astronomical interferometry. Our experimental demonstrator gives a typical S/N up to 19 over 1 minute exposure time on Antares. After demonstrating in laboratory that an up-conversion interferometer is able to provide good observables (Brustlein et al. 2008; Ceus et al. 2011), the next step of this study will take place on the CHARA interferometer to get fringes on an astronomical source.

ACKNOWLEDGMENTS

We would like to acknowledge the CFHT astronomical observatory, the Agence pour la Valorisation de la Recherche Universitaire du Limousin (AVRUL), the BQR University of Limoges, the ’Ohana team (Observatoire de Paris) and Alain Dexet for his advice and the realization of the mechanical parts.

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