Laboratory Demonstration of Spatial-Coherence Analysis of a Blackbody through an Up-Conversion Interferometer

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In the field of high resolution imaging in astronomy, we experimentally demonstrate the spatial-coherence analysis of a blackbody using an up-conversion interferometer in the photon counting regime. The infrared radiation of the blackbody is converted to a visible one in both arms of the interferometer thanks to the sum-frequency generation processes achieved in Ti-diffused periodically poled lithium niobate waveguides. The coherence analysis is performed through a dedicated imaging stage which mimics a classical telescope array analyzing an astrophysical source. The validity of these measurements is confirmed by the comparison with spatial-coherence analysis through a reference interferometer working at infrared wavelengths.

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In the framework of high resolution imaging, the use of aperture synthesis devices allows us to get the angular resolution required to extensively study the Universe. This kind of instrument consists of a telescope array which collects the light emitted by an astrophysical object. By mixing the waves collected by each telescope, we obtain an interferometric signal allowing us to measure the Fourier transform of the spatial intensity distribution of the source under study (Zernike–Van Cittert theorem [1]). This way, by changing the telescope basis, it is possible to sample the spectrum of the spatial intensity distribution. These data are either processed to retrieve an image of the object through reconstruction algorithms or directly used for model fitting [2,3].

At the present time, several instruments have been implemented to investigate the visible and near-infrared (NIR) spectral domains using such a method. On some of these devices (FLUOR [4,5] and AMBER [6]), the use of integrated optical components allows us to achieve very accurate and reliable measurements on astrophysical targets (Fig. 1). For example, using optical fibers to spatially filter the optical beams incoming from the telescopes allows us to trade off phase fluctuations due to atmospheric turbulence against intensity fluctuations that can be more easily monitored and corrected at the interferometer output.

In order to obtain detailed information on astronomical sources with a blackbody behavior (for example, exoplanets or astrophysical objects at the beginning or at the end of their lives), high resolution imaging is currently extending its capability towards the detection of optical waves in the midinfrared (MIR) and the far-infrared (FIR) spectral domains. However, these spectral domains are more challenging to investigate, as the required components (fibers, integrated optical components, and detectors) are either not available or have low performances. In order to overcome these limitations, a lot of technological developments are currently conducted to design optical components matching with the MIR and FIR spectral domain requirements [7–10].

In an alternative way, our research team investigates an original approach to this challenge. Instead of trying to develop a new instrumental chain to propagate, mix, filter and, more generally, process MIR or FIR light, we propose to shift a part of the long wavelength spectrum of the astronomical source to the visible while preserving its coherence properties using a sum-frequency generation (SFG) process. This nonlinear effect is intensively investigated in the fields of quantum communication [11–13], spectroscopy [14], and direct imaging [15–17]. It is known to be intrinsically noiseless [18] and can be used to up-convert a part of the spectrum of very faint sources.

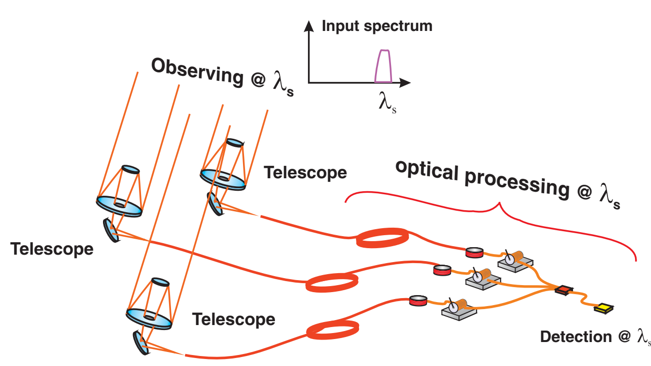

FIG. 1 (color online). Global scheme of a telescope array using fibered components to analyze the spatial coherence of an astronomical source at visible and infrared wavelengths.

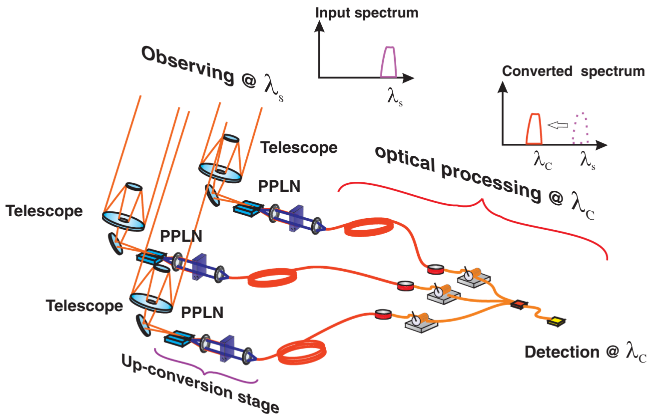

FIG. 2 (color online). Global scheme of the up-conversion interferometer dedicated to spatial-coherence analysis of an astronomical source (PPLN: periodically poled lithium niobate).

For ten years, we investigated the potential of the SFG process in the framework of spatial-coherence analysis for high resolution imaging. For this purpose, we have designed an interferometer with a stage of up-conversion from infrared to visible in each arm (Fig. 2). This way, after the light is collected by each telescope, the optical waves are shifted to a spectral domain where a very efficient optical chain can be used (optical fibers, couplers, detectors, etc.).

In the long term, this up-conversion interferometer will present two major advantages compared to the current or future classical aperture synthesis instruments dedicated to the analysis of MIR or FIR light. First, the possibility to use optical fibers after each SFG process allows us to achieve long-distance transport of the interferometric beams, which is not possible over hundreds of meters with current bulk optical components operating in the MIR and FIR spectral domains. This property would be of great use, for example, in the framework of a protoplanetary disk study, which needs both high resolution and good sensitivity at FIR wavelengths [19]. Second, as the SFG process is limited to a narrow spectral bandwidth (in the range of hundreds of picometers), such an instrument will benefit from a high spectral resolution, which is not available with a classical instrument without a strong limitation of its sensitivity. This feature would be relevant for spectroscopic studies like water ice and organics detection at MIR wavelengths [20].

In order to achieve proof-of-principle experiments with such an instrument, we have developed and characterized a laboratory up-conversion interferometer involving nonlinear integrated optical periodically poled lithium niobate (PPLN) components to convert 1.55 μm radiations to 630 nm in the visible domain. Working in the NIR spectral domain for these preliminary studies allows us to compare the results provided by the up-conversion interferometer with reference measurements achieved with reliable, calibrated NIR instruments using guided optics (for example, the MAFL [21]).

With this setup, we have previously analyzed NIR laser sources and demonstrated the preservation of the observables to be acquired (contrast and phase closure measurements) [22,23]. Moreover, we have recently successfully up-converted the starlight collected by a single small 8 in telescope and proceeded it through one single arm of the up-conversion interferometer [24] validating the sensitivity of this instrument for future on-sky proof-of-principle demonstration.

As a direct continuation of these previous demonstrations, we report in this Letter on the laboratory demonstration of the spatial-coherence analysis of a blackbody using an up-conversion interferometer. The aim of this work is to experimentally demonstrate that the SFG process can be applied to the detection of incoherent light sources with far less than one photon per spatiotemporal mode, while preserving its coherence properties. Since such a source emits light over a large spectral bandwidth, coherence analysis is only possible if the mutual coherence of the two converted optical fields is preserved through the instrument. This condition requires us to achieve very similar nonlinear processes on each arm of the up-conversion interferometer. To validate the results obtained through this experimental setup, they are compared to measurements achieved with a reference fibered interferometer working at infrared wavelengths.

We use a halogen bulb lamp as the blackbody source. Its spectrum is limited over a 10 nm bandwidth by an interference filter centered at 1550 nm. It is then coupled to a 50 μm core diameter multimode fiber. The output of this fiber acts as the thermal object that we want to spatially analyze. It provides a power $P_s \approx 60$ nW shared out over 100 spatial modes. To analyze the spatial coherence of such an object, we have implemented an experimental setup divided in two parts: the imaging stage and the interferometer.

The imaging stage mimics the telescope array analyzing the astrophysical source [Fig. 3(a)]. First, a polarizer selects the linear vertical polarization of the light under analysis. Then a lens associated with a beam splitter forms two images of the multimode fiber output plane, which are then spatially sampled thanks to two single mode fibers [Fig. 3(b)]. The relative position of these single mode fiber inputs is controlled by fine positioning modules. The translation of the fiber tips along the x axis allows us to scan the spatial mutual coherence function of the thermal object and acts as a change of the telescope basis (relative position of two telescopes) in the genuine configuration. The overall transmission of the imaging stage is in the range of 5×10^{-4} from the multimode fiber output to the output of one single mode fiber which samples the light under analysis. In this case, the large bandwidth of the source and the very low number of photons per spatiotemporal mode increase significantly the difficulty to retrieve the mutual coherence of the optical fields.

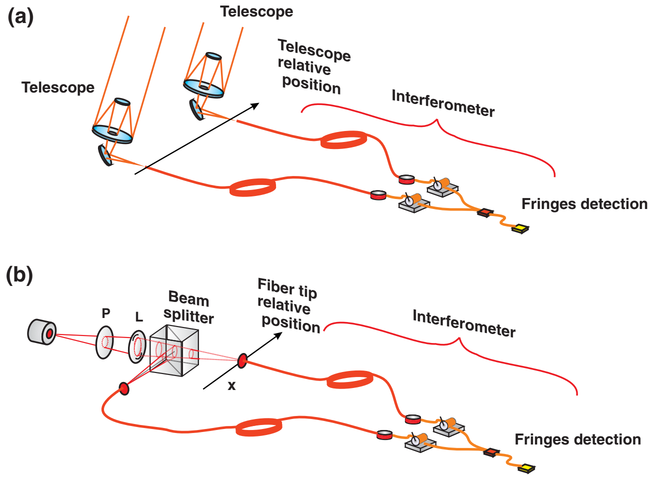

FIG. 3 (color online). (a) Classical spatial-coherence analysis through a telescope array. (b) Spatial-coherence analysis through the dedicated test bench used for the laboratory experiment on a blackbody source [P (polarizer), L (lens)].

Using this configuration, it is possible to test the actual effect of the SFG stage implemented in each arm of our up-conversion interferometer on the mutual coherence analysis of the thermal object. In our experiment, this function results from the modal distribution at the output plane of the multimode fiber. This spatial distribution is extremely difficult to model as being sensitive to all the source assembly. This way, we performed two different measurements: the first one by using a reference infrared interferometer and the second one by using the up-conversion interferometer. The two instruments are successively connected to the imaging stage output.

The reference IR interferometer is shown in Fig. 4. This instrument uses polarization maintaining single mode fibers at 1550 nm. In one interferometric arm, we have inserted a 12 cm stroke fibered delay line [25] to manage the optical path difference (OPD). To display the fringe pattern as a function of time, we temporally modulate this

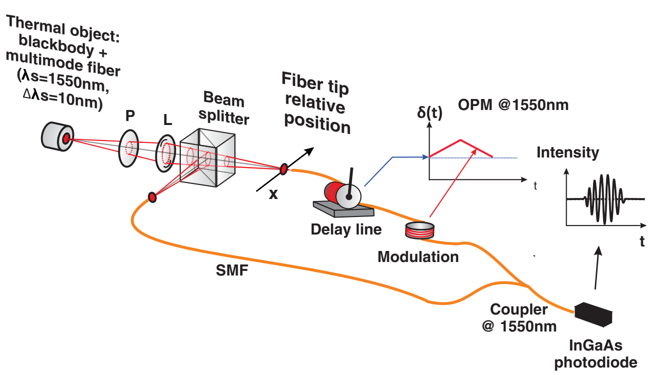

FIG. 4 (color online). Global scheme of the reference IR interferometer [P (polarizer), OPM (optical path modulation), L (lens), SMF (single mode fiber)].

OPD over a $\pm 5\ \mu$m span by means of an optical fiber modulator [26]. The interferometric mixing is achieved through a 2×2 fibered coupler at the interferometer output. The overall transmission of the reference IR interferometer is equal to 0.35 from the single mode fiber input of the instrument to the output of the coupler. This allows us to acquire the fringe patterns in classical analog operation mode using an InGaAs photodiode. The related contrast measurements obtained with this instrument are recorded and used as a reference.

The up-conversion interferometer is shown in Fig. 5. In both arms of this instrument, the blackbody infrared radiation collected at the imaging stage outputs is up-converted to visible wavelengths thanks to SFG processes. These quasiphase matched processes are achieved in both interferometric arms using 40 mm long specially designed Ti:PPLN waveguides. The quasiphase matched conditions are determined by the PPLN periodicity ($\Lambda = 10.85\ \mu$m) and temperature. Here, we use PPLN waveguides at a temperature equal to 90 °C, allowing us to convert a 1550 nm radiation to 630 nm, thanks to the energy supplied by a laser pump source around 1064 nm. The conversion efficiency spectral bandwidth of these PPLN crystals is equal to 0.3 nm. As the up-conversion interferometer and the reference one work on different spectral bandwidths (0.3 versus 10 nm, respectively), we took care to set the mean OPD value very close to zero in order to become insensitive to this spectral bandwidth difference. Note that in this last configuration, the narrow spectral bandwidth related to these SFG processes allows us to reach a high spectral resolution at the cost of a decrease of the global power conversion efficiency. In addition, the SFG process leads to a converted signal with a higher coherence length than the incoming infrared signal. This reduces significantly the constraint on the optical path equalization in the interferometer and makes it easier to improve the sensitivity of the instrument by time integration of the signal power spectral density. This configuration is well suited to the detection of very faint infrared astronomical sources [24].

On this instrument, fibered wavelength division multiplexers are used in both interferometric arms to mix the infrared radiation under analysis with the light emitted at $\lambda_p = 1064.5$ nm by the Nd:YAG laser pump source ($P_p = 20$ mW at each SFG process input). These waves are then injected into the PPLN waveguides to perform the up-conversion processes. In order to preserve the mutual coherence of the two optical fields propagating in the fibered arms, the two nonlinear processes have to be identical. Hence, a fine-tuning of the conversion efficiency curves associated to each SFG process is necessary. This functionality is achieved here through the crystal temperature control with a dedicated homemade servo system allowing a 0.01 °C accuracy. The converted signal in each arm is spectrally filtered with a dispersive prism and an interference filter centered at 630 nm ($\Delta\lambda = 40$ nm) for

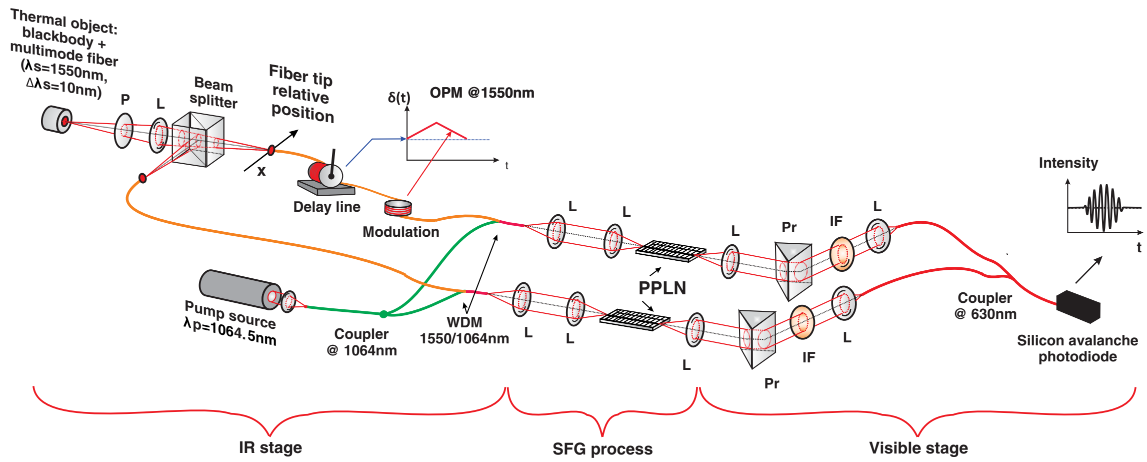

FIG. 5 (color online). Global scheme of the up-conversion interferometer [OPM (optical path modulation), *L* (lens), WDM (wavelength division multiplexer), IF (interference filter), Pr (prism), *P* (polarizer)].

rejecting any residual infrared or parasite signal as the potential pump second harmonic radiation generated by a nonphase matched process in the waveguides. These up-converted beams are also spatially filtered through single mode fibers at 630 nm, and the interferometric mixing is obtained through a 2×2 single mode polarization maintaining fibered coupler.

The overall transmission of the up-conversion interferometer is in the range of 5×10^{-3} from the infrared fiber input of the instrument to its output in front of the detector. However, this value can be strongly improved for future experiments thanks to the use of fibered PPLN waveguides [27]. From this result and the coherence bench transmission, the mean flux on the detector is only hundreds of photons per second. To achieve the detection of fringe patterns at this power level, we used a silicon avalanche photodiode (Si-APD) working in the photon counting regime with a 70% detection efficiency and a dark count rate of 65 counts/s.

Before using the interferometer, we have conducted preliminary measurements to characterize additional noises that could be generated through the SFG processes on the instrument. The main contribution is due to the laser pump source supplying each nonlinear process [28,29] and could lead to a strong limitation of the signal-to-noise ratio (SNR). This way, we performed two different measurements of the noise at the interferometer output when the pump was off and on. In both cases, the noise count rate was equal to the dark count of the detector. This result infers that in this experimental configuration, the SFG processes do not generate any significant noise which could harm the SNR of the instrument. The detector dark count is the only noise source to take into account.

Using the reference and the up-conversion interferometers, we performed the spatial-coherence analysis of the thermal object. The results of this experimental study are shown in Fig. 6. The fringe contrast evolution is measured as a function of the fiber tip position x for the two experimental configurations (reference and up-conversion interferometer). Each contrast and related standard deviation reported here has been computed through the acquisition of 500 frames of 100 ms duration each. Each measurement is corrected from the photometric imbalance between the two interferometric arms of the instrument.

We measured a maximum contrast equal to 89.1% with the reference interferometer and to 89.3% with the up-conversion one. For these two measurements, the maximum contrast degradation against its theoretical value (100%) is due to differential defects on the imaging stage. The relative difference between the two curves fitting the experimental data is lower than 3% at half maximum. The very good agreement between these measurements clearly demonstrates that the spatial coherence of a blackbody source with far less than one photon per spatiotemporal

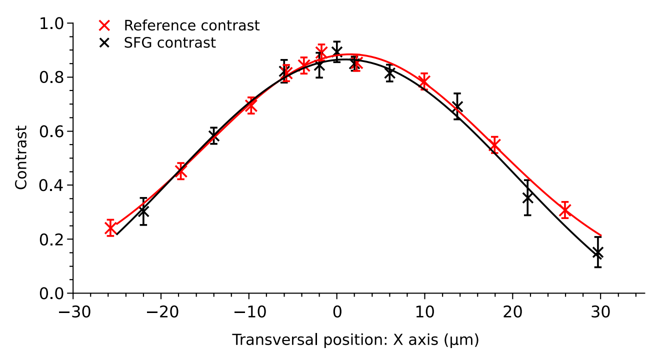

FIG. 6 (color online). Fringe contrast evolution versus the fiber tip relative position x for the two experimental configurations [red crosses (reference IR interferometer measurements), black crosses (up-conversion interferometer measurements)]. The red curve is the numerical fit of the reference contrast measurements. The black curve is the numerical fit of the SFG contrast measurements.

mode can be investigated using an up-conversion interferometer.

In conclusion, we have carried out an experimental study on the application of an up-conversion process to high resolution imaging in astronomy. By comparing our experimental results with a reference one obtained with the reference IR interferometer, we have clearly demonstrated the possibility to achieve the spatial-coherence analysis of a blackbody through SFG processes implemented on each arm of the interferometer.

After this laboratory demonstration, the next step will consist of an on-sky proof-of-principle experiment using an up-conversion interferometer coupled with a telescope array to achieve a spatial-coherence analysis on a real astrophysical object. We are planning to test the up-conversion interferometer on the CHARA telescope array in the coming years. This study will then be carried out with astrophysical light around 1550 nm to benefit from the available technology in the telecom window before being extended to longer wavelengths in the MIR and FIR spectral domains.

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