Multicolor upconversion imaging by Adiabatic Sum Frequency Conversion

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Upconversion imaging, where mid infrared (IR) photons are converted to visible and near IR photons via a nonlinear crystal and detected on cheap and high performance Silicon detectors, is an appealing method to address the limitations of thermal sensors which are expensive, often require cooling and suffer from both limited spectral response and limited spatial resolution as well as poor sensitivity. However, phase matching severely limits the spectral bandwidth of this technique therefore requiring serial acquisitions in order to cover a large spectrum. Here we introduce a novel upconversion imaging scheme covering the mid-IR based on adiabatic frequency conversion, which allows robust frequency conversion of ultrabroad bandwidth spectral range. We present a proof of concept of mid-IR multicolor imaging and demonstrate simultaneous imaging on a CCD camera of radiation spanning a spectrum from 2 to 4 \(\mu m\).

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1. INTRODUCTION

Spectrally resolved imaging (i.e. ‘color imaging’) in the infrared spectral region is a much-valued functionality with applications in remote sensing, medical imaging and environmental monitoring owing to the mid-infrared signatures of vibronic states in characteristic organic and chemical compounds. To date, the most widely used Infrared cameras [1] in the Mid to long-wave-length infrared region are based on materials such as Indium Antimonide (InSb) and Mercury Cadmium Telluride (MCT). However, these materials are expensive to process, often require cooling and suffer from both limited spectral response and limited spatial resolution as well as poor sensitivity. As a result, there is a strong demand for practical schemes that efficiently convert mid- and near-infrared light to the visible regime, where high-performance, low-cost CCD sensors are widely available. Many methods have been explored so far, including nonlinear upconversion [2] and photochemical upconversion by triplet states [3]. More recently, nonlinear conversion of incoherent images has been demonstrated, achieving single-photon sensitivity, high resolution imaging of mid-IR signals with a visible camera [4, 5]. However, like any conventional nonlinear optical conversion, these exciting methods suffer from the phase-mismatch challenge, i.e. the lack of inherent momentum conservation between the interacting waves, which requires an implementation of a phase matching compensation technique [6]. This limitation results in an efficient conversion only over a very narrow spectral band, where the phase mismatch can be compensated, and therefore these methods are found to be unsuited for broad-spectral imaging. In recent years, a new concept in nonlinear optics has been developed to tackle the problem of efficient conversion of broad optical bands. The concept, which is known today as adiabatic frequency generation (AFG), was pioneered in Refs. [7, 8], and allows efficient, robust and scalable transfer of broadband, visible and near-IR lasers to the mid-IR optical regime and vice versa. In the past few years this method has been successfully demonstrated and was shown to outperform the currently available mid-IR ultrashort sources, allowing the realization of high-energy, octave-spanning mid-wave IR pulsed source that can reach up to sub two-cycle temporal resolution in the mid-IR covering the 2-5 \(\mu m\) spectral region [9–11]. Yet this technique has been applied only to the generation of coherent sources and has not been used as an imaging platform. Here, we apply the Adiabatic Sum Frequency conversion [12, 13] process...
to convert broadband mid-Infrared coherent images into the visible spectral range and demonstrate broadband color imaging spanning one octave in the Mid-IR (2-4 µm) using low-cost, high sensitivity, fast, and robust visible CCD, all without having to tune the converting crystal phase matching conditions. We also discuss the parameters that affect our scheme spatial resolution performances. Our method paves the way to full spectrally resolved single-shot imaging of noncoherent mid-infrared scenes with cheap and high performance Silicon based detectors.

2. EXPERIMENTAL METHODS

We demonstrate our ASFG based imaging scheme in a fully coherent experiment, shown in Fig.2 (a), where we split a 2 MHz repetition rate 150 femtosecond pulse at 1030 nm with 20 nm full width half-maximum (FWHM) to first generate different mid-IR wavelengths (one at a time) using Optical Parametric Generation (OPG) in a MgO:PPLN crystal with 7 different periods, allowing to tune the generation of mid-IR in the range 2 – 4µm. The other beam is delayed and used in subsequent ASFG as described below. The generated mid-IR radiation is collimated and illuminates a combined resolution / distortion test mask (Fig.2 (b)) that includes a 1951 USAF pattern, a sector star, concentric circles, grids, and Ronchi rulings. The mid-IR illuminated mask is imaged in a 4f system that also includes telescope optics (not shown in Fig. 2) to reduce the physical size at the Fourier Plane where the ASFG converting crystal is placed in order to avoid spatial frequencies filtering due to the limited crystal aperture size. The delayed pump is combined with the mid-IR radiation onto the the ASFG crystal via a Sapphire window. The mid-IR object Fourier transform is then upconverted in the ASFG crystal when The delay line allows the temporal overlap between the pump and the mid-IR radiation. As seen in Fig.2 (c) the ASFG crytal designed conversion efficiency allows a broad upconversion of the mid-IR into the visible-near IR spectral region. Finally a last lens is used to complete the imaging task by Fourier transforming the now visible Fourier plane into a color CCD camera where the multicolor visible image can be detected.

Fig. 1. Comparison between state-of-the-art method for imaging in the mid-IR (a) Bolometers and thermal imager are the most widely used methods for mid-IR sensing. However its sensors' materials severely limit the sensitivity, spatial resolution and spectral bandwidth. The obtained image doesn’t usually contained spectral information. (b) Upconversion imaging addresses some of the thermal imaging limitations by converting the mid-IR radiation to a visible-near-IR, which is being detected by a widely available, fast and sensitive Silicon based detector. This technique however is impeded by the periodical polling of the nonlinear crystal (PPLN) that imposes a narrow spectral bandwidth to achieve an efficient upconversion. As a result, the crystal quasi-phase matching needs to be tuned by either tuning the angle (θ) between the crystal and the incoming beam or the crystal’s temperature and images are acquired sequentially for each tuning parameter [θ₁, θ₂, θ₃, ...] in order to image different parts of the mid-IR spectrum. (c) in a sharp contrast, our demonstrated imaging scheme based on adiabatic Sum Frequency Generation (SFG) is able to fully convert simultaneously a wide spectrum, here covering from 2 to 4 µm, without having tune any parameter and to sequentially acquire. Using a visible color camera we can therefore image the mid-IR and translate in a one-to-one relationship the “colors” or signatures in the mid-IR to colors in the visible-Near infrared.

3. RESULTS AND DISCUSSIONS

Based on the setup described above, we first demonstrated single wavelength imaging ability of our scheme in the range of 2 - 4 µm for several wavelengths in this range. Several of these
Measurements are presented in Fig. 3. In Fig. 3(b) we show the mid-IR spectrum obtained via OPG with 3 different periods spanning the 2 µm to 4 µm spectral region. Fig. 3(a) shows the ASFG upconverted images obtained on the visible CCD camera of each of the OPG-generated mid-IR radiations. The character “3” from the USAF 1951 target is clearly visible for each of the 2, 3, and 4 µm wavelengths. The upconverted spectrum of each of these cases is shown in Fig. 3(c) and demonstrate a spectral span from 690 nm to 822 nm in the visible-near-IR. It is essential to stress that no change whatsoever to ASFG crystal or to the optics has been introduced to obtain these different images, therefore already demonstrating the efficient and robust conversion capability of the ASFG based imaging. This is in stark contrast standard upconversion imaging, where the quasi-phase-matching of the upconverting crystal needs to be tuned, preventing the simultaneous imaging of a broad mid-IR spectrum.

(a) 3 images obtained on the color CCD camera visible via ASFG
(b) The original mid-IR spectrum of the radiation impinging on the mask.
(c) The visible spectrum after ASFG upconversion of each of the presented mid-IR wavelengths. It is important to stress that tuning whatsoever of the ASFG crystal or optics has been necessary between the different mid-IR wavelengths.

We further demonstrate the simultaneous upconversion imaging of multiwavelength mid-IR radiation in our scheme, a feat not accessible in the standard quasi-phase-matching limited upconversion imaging. The simultaneous imaging of the mask illuminated with a mid-IR radiation containing both from 2 and 4 µm (Fig. 4(b)) is shown in Fig. 4(a). While both wavelengths are converted with similar efficiencies, the two wavelengths are seen with different magnification and therefore they give rise to two distinctive images on the visible sensor. Several reasons are accountable for this effect. First of all, there is inherently a different scaling of images upconverted from different mid-IR wavelengths [14]:

\[ I_{up} = \frac{16\pi n_p^2 P_{Gauss} L^2}{n_\mu n_1 n_2 \epsilon_0 f_3^2 f_2^2} \Gamma_{2,4} \lambda_1 f_3 \left( \lambda_2 f_4^2 \lambda_2 f_4 \lambda_2 f_4 \right) \]

Where \( \lambda_1 \) is the mid-IR wavelength, \( \lambda_2 \) is the corresponding upconverted visible-near-IR wavelength and \( n_p \) is pump refractive index. From this relation, we observe that for different wavelengths in the mid-IR, which are upconverted to different wavelengths in the visible-near-IR, the scaling will be different: \( I_{up} \sim I_{object} \left( \frac{\lambda_1 f_3}{\lambda_2 f_4} \frac{\lambda_2 f_4}{\lambda_2 f_4} \right) \). Moreover, in our proof-of-concept setup, the optics has not been optimized to account for chromatic aberrations. Also, it is reasonable to suggest that the incoming wavelength comes in with some angle to the first imaging lens \( f_3 \). As we show in the sketch in Fig. 4(c), this will induce lateral chromatic aberration and different wavelengths will result in images that do not overlap. Moreover, the visible wavelengths are generated at different locations on the optical axis at the ASFG crystal, resulting in different accumulated phases for different spectral components, which will in turn result in blurred image for some wavelengths while other are seen sharply. We believe that an optimized and achromatic set up that takes into account all the above considerations will result in images of the same magnification and spatial overlap over a broad bandwidth. These chromatic aberrations however don’t impact the observation that the ASFG upconversion scheme is able to simultaneously convert and image (with aberrations) a multicolor mid-IR scene spanning 2 and 4 µm.

![Fig. 4. Simultaneous broadband imaging upconversion of the letters “SECTOR” (a) The image showing the 690 nm (red) and 820 nm (white) image being formed simultaneously with comparable intensity and therefore efficiency. (b) The mid-IR spectrum that was passed through the mask. (c) Illustration of lateral chromatic aberration.](image)

Finally, we examine the ASFG based imaging resolution performance for a specific wavelength in the mid-IR. Here for the purpose of increased resolution, the magnification of the system is increased with \( f_4 = 250 \) mm. In Fig. 5, the image for upconverted mid-IR at 3.5 µm to the visible, for three targets is shown. In Fig. 5(a), the target mask is 10 Circles with Radii from 100 µm to 1000 µm in 100 µm Intervals. In the detected image we can notice these different radii. In Fig. 5(b), the target mask is composed of 36 Bars of varying widths rotated through 360°, 10 µm radius center circle and ten concentric circles with Radii from 50 µm to 500 µm in 50 µm intervals. We observe that in the image the bars are seen very clearly. However the inner radius circles are not clearly resolved. In Fig. 5(c) the target mask is USAF target group 3. All the lines are seen clearly. The thickest line is beside the label “6” with thickness of 35.08 µm. It is important to note that the main limit to the resolution is the fact that the crystal aperture acts as a spatial filter, cutting out high spatial frequencies. In our situation, the size of Fourier distribution in the Fourier plane is larger then the crystal aperture, there-fore high spatial frequencies are filtered, resulting in limited resolution. Bigger aperture ASFG crystal are still challenging to manufacture but will provide a viable way to increase the spatial resolution.
Fig. 5. Resolution examination of the ASFG based imaging, at $\lambda = 3.5 \ \mu m$. (a) 10 Circles with Radii from 100 $\mu m$ to 1000 $\mu m$ in 100 $\mu m$ Intervals. (b) 36 Bars through 360°, 10$\mu m$ radius center circle and ten Concentric circles with radii from 50 $\mu m$ to 500 $\mu m$ in 50 $\mu m$ Intervals. (c) group 3 from USAF target. For example, the line width in (c) 6 is 35.08 $\mu m$. We note that the resolution is primarily impacted by the limited aperture size of the ASFG crystal.

4. CONCLUSIONS

In this work, we have shown a simultaneous multicolor (spanning 2 $\mu m$ to 4 $\mu m$) imaging scheme onto a standard visible camera based on the efficient and ultrabroadband ASFG method and without the need to change any parameter in the ASFG optics and phase matching conditions. Furthermore, we show a proof-of-concept of mid-IR multi-color imaging onto a standard color CCD camera. We believe that such method will be useful for broadband mid-IR imaging and spectroscopy in a wide range of applications - from astronomy, remote sensing, environmental monitoring, biological and chemical identification and more.

REFERENCES

1. M. Vollmer and K.-P. Möllmann, Infrared Thermal Imaging, Fundamentals, Research and Applications (Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2017).
2. R. W. Boyd and M. O. Scully, “Efficient infrared imaging upconversion via quantum coherence,” Appl. Phys. Lett. 77, 3559–3561 (2000).
3. T. N. Singh-Rachford and F. N. Castellano, “Photon upconversion based on sensitized triplet–triplet annihilation,” Coord. Chem. Rev. 254, 2560–2573 (2010).
4. J. S. Dam, C. Pedersen, and P. Tidemand-Lichtenberg, “Theory for upconversion of incoherent images,” Opt. Express 20, 1475–1482 (2012).
5. J. S. Dam, P. Tidemand-Lichtenberg, and C. Pedersen, “Room-temperature mid-infrared single-photon spectral imaging,” Nat. Photonics 6, 788–793 (2012).
6. R. W. Boyd, “Nonlinear Optics 3rd edn (San Diego, CA: Academic),” (2008).
7. H. Suchowski, D. Oron, A. Arie, and Y. Silberberg, “Geometrical representation of sum frequency generation and adiabatic frequency conversion,” Phys. Rev. A 78, 063821 (2008).
8. H. Suchowski, B. D. Bruner, A. Ganany-Padowicz, I. Juwiler, A. Arie, and Y. Silberberg, “Adiabatic frequency conversion of ultrafast pulses,” Appl. Phys. B 105, 697–702 (2011).
9. H. Suchowski, P. R. Krogen, S.-W. Huang, F. X. Kärtner, and J. Moses, “Octave-spanning coherent mid-IR generation via adiabatic difference frequency conversion,” Opt. Express 21, 28892–28901 (2013).
10. H. Suchowski, G. Porat, and A. Arie, “Adiabatic processes in frequency conversion,” Laser & Photonics Rev. 8, 333–367 (2014).
11. P. Krogen, H. Suchowski, H. Liang, N. Flemens, K.-H. Hong, F. X. Kärtner, and J. Moses, “Generation and multi-octave shaping of mid-infrared intense single-cycle pulses,” Nat. Photonics 11, 222–226 (2017).
12. H. Suchowski, A. Arie, D. Oron, V. Prabhudesai, and Y. Silberberg, “Robust adiabatic sum frequency conversion,” Opt. Express 17, 12731–12740 (2009).
13. A.-L. Calendron, F. X. Kärtner, H. Suchowski, and H. Cankaya, “Highly efficient broadband sum-frequency generation in the visible wavelength range,” Opt. letters 39, 2912–2915 (2014).
14. C. Pedersen, E. Karamcedovic, J. S. Dam, and P. Tidemand-Lichtenberg, “Enhanced 2d-image upconversion using solid-state lasers,” Opt. Express 17, 20885–20890 (2009).