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Spectral Imaging by Upconversion

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Abstract. We present a method to obtain spectrally resolved images using upconversion. By this method an image is spectrally shifted from one spectral region to another wavelength. Since the process is spectrally sensitive it allows for a tailored spectral response. We believe this will allow standard silicon based cameras designed for visible/near infrared radiation to be used for spectral images in the mid infrared. This can lead to much lower costs for such imaging devices, and a better performance.

Keywords: Upconversion, spectral imaging.

1 Introduction

Imaging with spectral information has many potential applications. This includes medical imaging, cleantech, combustion analysis, and food imaging. Here we present how a new technology can be used to extend the working range of silicon based cameras far beyond their normal wavelength working range. This is done by upconversion, which is a process often used to convert the wavelength of lasers. This is for example used in green laser pointers where 2 near infrared laser photons at 1064 nm combine forming one green 532 nm photon with twice the energy. The same principle can be applied where two different wavelengths are mixed inside a nonlinear crystal, generating a third wavelength as the sum energy (or frequency, if you will). Under the right circumstances, this sum frequency generation will even be able to conserve image information existing at the input wavelengths. This process can even occur if one of the input wavelengths is incoherent light and the other a powerful laser.

Work on image upconversion was an active research field in the 1960's and 1970's. Around 1980 the field was abandoned, since the quantum efficiency (QE) of the process never exceeded $2 \cdot 10^{-7}$ and the obtained images had very low resolution not exceeding 20x20 image elements [1-7]. Recently [8], we demonstrated a vast increase in the Quantum efficiency and resolution obtainable in image upconversion.

[1] Please note that the LNCS Editorial assumes that all authors have used the western naming convention, with given names preceding surnames. This determines the structure of the names in the running heads and the author index.

In fact, we increased the QE by 1000 (to 0.02 %), and the amount of image elements by a factor 500 over previous work in the field (to 200x1000 image elements). This gives reason to believe that the process can be improved to be usable for many different applications, as pointed out in a News & Views story [9] about our previous work.

2 The experimental details

The working principle of our first image conversion module is illustrated in Fig. 1.

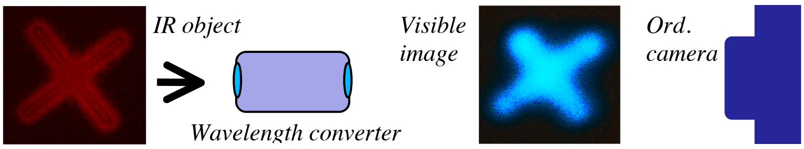


Fig. 1. The working principle of the image wavelength converter. Light from an infrared object is passing through a wavelength converter module which transforms the wavelength of the light to a new, shorter, wavelength. This wavelength can be captured by an ordinary camera.

Photons containing image information at a wavelength, λ1 are mixed with a laser with wavelength λ2, to form upconverted photons at the sum frequency, λ3. See Eq. 1.

$$\frac{1}{\lambda_1}+\frac{1}{\lambda_2}=\frac{1}{\lambda_3} \tag{1}$$

To obtain efficient conversion the phase matching condition must be satisfied. See eq. 2.

$$k_3 = k_1 + k_2 + K_{QPM} \tag{2}$$

k_i is the wavenumber of the photons, and K_{QPM} is the quasi phase matching parameter, which is $K_{QPM} = 2\pi/PP$, where *PP* is the poling period of the nonlinear crystal. Since the poling period can be designed to specifications, it is possible to design phase matching of any wavelengths, as long as the nonlinear crystal is transparent to the three involved wavelengths.

The module accepts radiation at one wavelength regime with image information, and converts that radiation to another wavelength. This wavelength-converted image has been spectrally filtered by the nonlinear process, and can be detected with a standard camera.

Details of the experimental setup can be found in reference [8]. The key ingredients are a nonlinear crystal placed within an intense laser field. The intense laser beam is generated by setting up a resonant laser system (the laser photons are "recycled" passing through the crystal many times using an intra cavity set-up). This makes it possible to obtain very high laser powers, by use of a comparatively low power pumping laser. In the present setup the phasematched wavelength can be tuned either by tuning the temperature or other parameters in the phasematch condition. By choosing a suitable poling period any wavelength, for which the nonlinear crystal is transparent, can be upconverted.

Since the conversion efficiency is proportional to the laser power, the system optimized to provide maximimum intracavity laser power. This is done by minimizing the losses, by using laser mirrors with very high reflectivity. Furthermore the nonlinear crystal is inserted in the laser cavity at Brewster angle minimizing reflection losses. Since the Brewster angle is nearly identical for the incoming and the generated wavelength, the reflection losses are minimal.

3 Designing the bandwidth of the upconverter

In previous work we have demonstrated how very narrow or broad acceptance bandwidths can be obtained. Basically this is done by choosing the right combination of nonlinear crystal and mixing laser wavelength. We have designed a simple method to calculate how to optimize the phase match condition for broad band and narrow band upconversion respectively. The obtainable bandwidth will depend on the length of the nonlinear crystal. In the case of broadband phase matching (which happens when the wavelength dependence of phase match condition is zero in the first order approximation), it can be shown that the actual phase matched bandwidth is inversely proportional to the square root of the length of the crystal. E.g. this means that a four time's longer crystal has half the wavelength acceptance. In case of narrowband phase matching, the bandwidth is inversely proportional to the length of the nonlinear crystal.

By choosing the correct mixing laser wavelength it is thus possible to design a system with desired bandwidth acceptance parameters. By having several different poling periods, e.g. side by side within the same nonlinear crystal it is possible to tune the observed spectral wavelength [10].

4 Image enhancement

The loss of high frequency image resolution associated with imaging through a Gaussian aperture, can to some extent be corrected for. We know from the diffraction theory exactly what the optical transfer function (OTF) and point spread function (PSF) are.

The optical transfer function (OTF) and point spread function are related to each other according to Eq. 3.

$$PSF = FT\{OTF\} \tag{3}$$

FT is the Fourier transform. The PSF can be understood as the spatial distribution of upconverted photons originating from a point source. It can be shown that the OTF is the actual shape of the mixing laser (λ_2). This implies that if high spatial resolution is desired, one should have a large beam diameter inside the nonlinear crystal.

Since the OTF is Gaussian, we can correct for the loss of high frequency information. In fig. 2 we demonstrate the image enhancement possible from applying a wiener filter to deconvolve the acquired upconverted image.

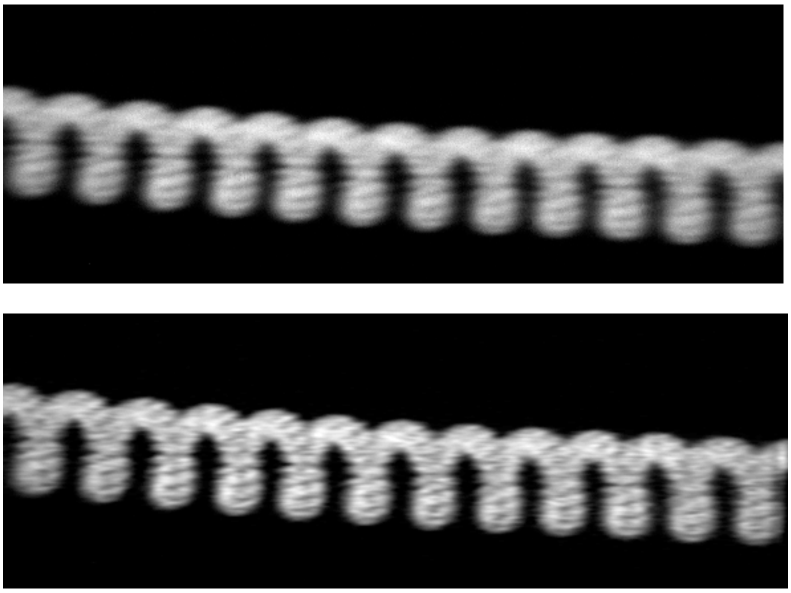
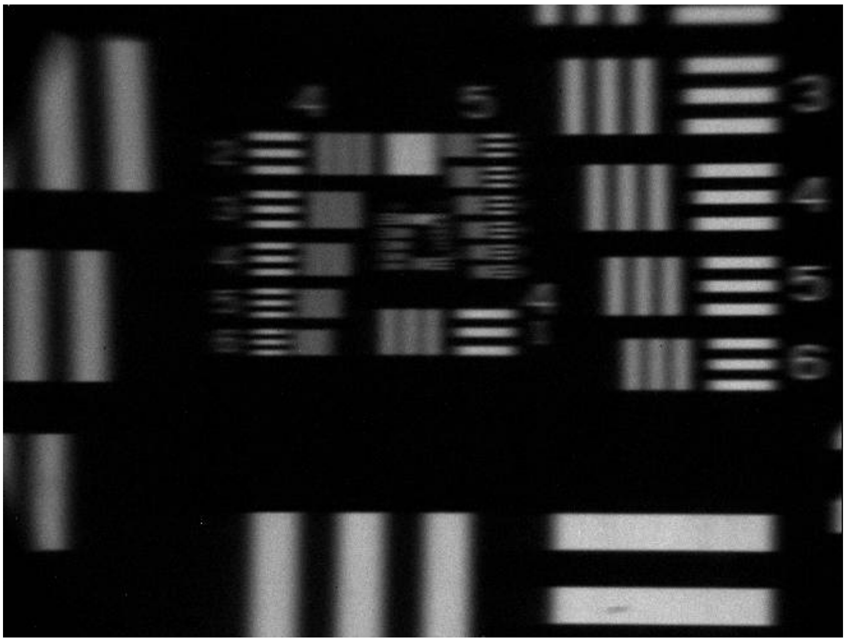


Fig. 2. Image of the filament in a light bulb. Light is upconverted from 765 nm (0.25 nm bandwidth) to 488 nm. The upper image shows the acquired image. The lower shows the same image after wiener filtering.

The ability of the wiener filter to increase the contrast and resolution is further demonstrated by applying the same filter to a resolution target as illustrated in Fig. 3.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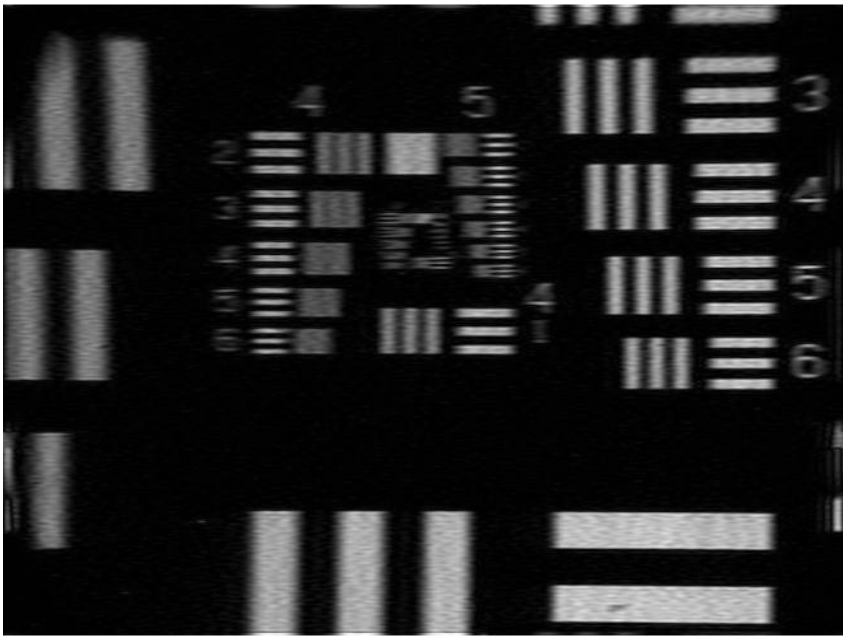
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Fig. 3. Before and after image restoration. Clearly the lower image (Image restored) has better contrast and the resolution is also improved at the cost of a reduced signal to noise ratio.

As can be seen from Fig. 3 the image restoration results in higher resolution. In the original image vertical line pattern 4.2 is the smallest resolvable vertical lineset. In the image enhanced version pattern 4.3 can be resolved. This corresponds to 12 % better resolution. The contrast is also much improved.

5 Conclusion

To conclude, we have demonstrated a versatile novel method for wavelength conversion of light while preserving image information. There is a large degree of freedom in how the light is converted, as the spectral response can be designed with a quite large degree of freedom. Since the process does lead to some loss of spatial resolution, we have demonstrated how this loss can be minimized by application of image restoration techniques.

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