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System and method for detection of infrared object light

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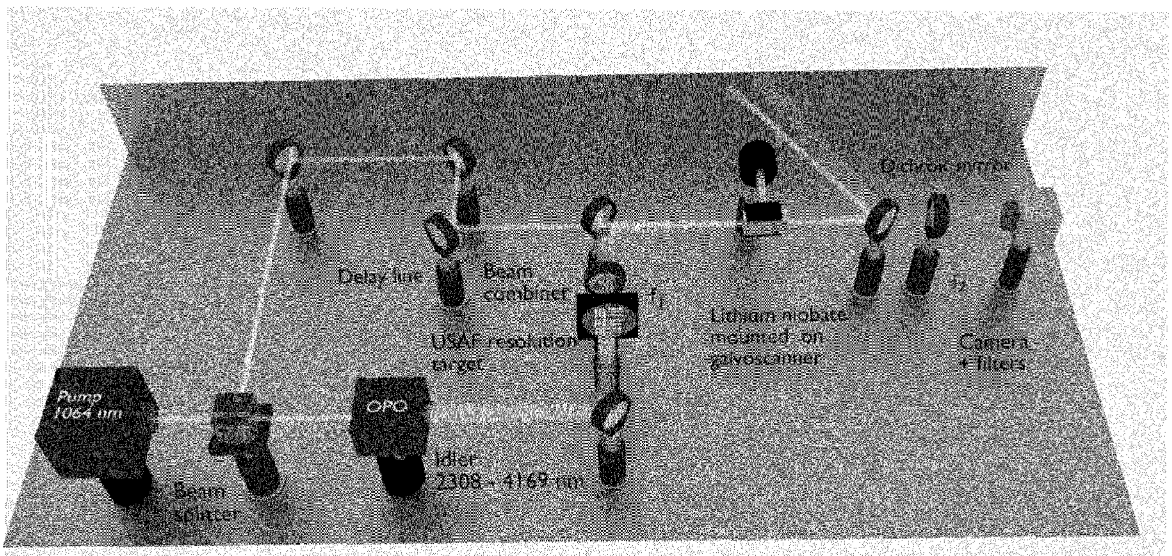

Fig. 1

(57) Abstract: The present disclosure relates to imaging of infrared light employing non-linear frequency upconversionand scanning of phase match condition to obtain a large field- of-view. Video frame rate direct detection of infrared object light can thereby be realized. One embodiment relates to a system for detection of infrared object light, the system comprising an non-linear medium configured for receiving 1) monochromatic infrared object light, and 2) seed light, and mixing the monochromatic infrared object light, and the seed light for frequency upconversion of the monochromatic infrared object light inside the non-linear medium, and a detector unit for imaging the upconverted object light, wherein system is configured to vary the phase match condition of the non-linear medium during image acquisition in the detector unit such that acquisition of one image in a sequence of images corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

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System and method for detection of infrared object light

The present disclosure relates to imaging of infrared light employing non-linear frequency upconversion and scanning of phase match condition to obtain a large field-of-view. Video frame rate direct detection of infrared object light can thereby be realized.

Background of invention

Hyperspectral imaging in the mid-infrared (mid-IR, approx. 2-20 pm) spectral range is an emerging technology utilized for a multitude of applications, but its full potential is prevented by the lack of sensitive mid-IR detectors. Nonlinear frequency upconversion offers a promising alternative to direct detection for room-temperature mid-IR spectroscopy and hyperspectral imaging.

Mid-IR hyperspectral imaging is applied in diverse fields such as medical diagnostics, environmental monitoring, geology for mineral identification and within the food industry. The widespread applicability of the mid-IR wavelength range is intimately linked to nature-given properties of molecular absorption and includes the following main categories; Vibrational spectroscopy (1) used for unique identification of complex molecules such as food or tissue, Gas spectroscopy (2) characterized by fundamental band interaction between mid-IR light and most gaseous molecules including environmental gasses such as CH_4, $C0_2$, NOx and SOx, and sensing of heat radiation from room temperature objects (3).

Despite all the virtues of mid-IR spectroscopy and imaging, one problem is the lack of sensitive, fast and cost-efficient detectors and cameras working at room temperature. One example is Fourier Transform Infrared (FTIR) spectroscopy that nowadays is the preferred technique for hyperspectral imaging in the mid-IR spectral range. A major limitation of FTIR imaging is that the cameras used for the mid-IR detection are predominantly based on MCT (HgCdTe), InSb or microbolometers, which are expensive and require cryogenic cooling. Moreover, for hyperspectral imaging, large data storage and complicated post-processing software is currently needed to generate useful data [1].

Nonlinear frequency upconversion provides an alternative route to fast, room-temperature mid-IR spectroscopy and imaging, due to its orders-of-magnitude higher sensitivity and speed compared to direct mid-IR detectors [2]. Nonlinear frequency upconversion is based on shifting the object light from the mid-IR region to the near visible spectral region where detectors are better developed and there is less thermal noise. The frequency shift is typically obtained by sum frequency mixing with a laser, resulting in a simple shift of the frequency while maintaining the spectral content for subsequent detection.

Summary of invention

A significant drawback in previous demonstrations of hyperspectral upconversion imaging has been the need for extensive post-processing which is required to obtain a large field of view (FoV), which in turn prohibits its use for real-time video-frame-rate imaging [[3]-[5]]. One purpose of the present disclosure is to circumvent this drawback.

The present invention addresses this issue by skipping the perception of hyperspectrality and reducing the bandwidth of the illumination light source to be substantially monochromatic. The field of view of the detected signal can be drastically increased by scanning and/or varying the phase match condition of the non-linear medium wherein the upconversion takes place, e.g. by (controlled) scanning or variation of a non-linear crystal as the non-linear medium. Direct detection can then be provided by synchronizing phase match scanning with camera frame integration, for example such that one scan of the phase match condition to obtain the large field of view corresponds to one frame in the camera. Hence, the phase match condition of the non-linear medium can be varied during image acquisition in a detector unit such that acquisition of one image (in a sequence of images) corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

One embodiment of the present disclosure therefore relates to a system for detection of infrared object light, the system comprising an non-linear medium, such as a non-linear crystal, configured for receiving 1) object light, and 2) seed light, e.g. object light in the form of monochromatic infrared light, and mixing the monochromatic infrared object light and the seed light for phase matched frequency upconversion of the monochromatic infrared object light inside the non-linear medium. A detector unit can then be provided for imaging the upconverted object light, a detector unit, such as a digital camera, such as a digital video camera, using CCD or InGaAs technology. The system can then advantageously be configured to scan and/or vary, e.g. periodically in the time-domain, the phase match condition of the non-linear medium. If the scanning is provided in synchronization with image integration in the detector unit, for example such that one period, or an integer number of periods, of phase match scanning corresponds to acquisition on one image in a sequence of images, direct detection of infrared object light can be provided. Scanning / variation of the phase match condition in the non-linear medium is possible by varying any one of several parameters that changes the indices of refraction, such as electric field (electro-optic effect), stress, temperature, or orientation. During this scanning / variation, different parts of the image are phase-matched and, hence, upconverted.

A further embodiment relates to a method for detection of infrared object light comprising the steps of mixing monochromatic infrared object light with seed light in a non-linear medium, such as a crystal, thereby frequency upconverting the monochromatic infrared object light by means of phase matching in the non-linear crystal, varying the phase match condition of the non-linear medium to increase the field of view of the object light, and imaging the upconverted object light, e.g. by means of a CCD camera, such that acquisition of one image in a sequence of images corresponds to image integration over a plurality of phase match conditions of the non-linear medium. The presently disclosed method thereby allows for increased field-of-view (direct) detection of infrared object light. The presently disclosed method can incorporate any of the features listed herein for the presently disclosed system for direct detection of infrared object light. The mixing in the non-linear medium can be synchronous between object light and seed light in case of pulsed light sources.

The non-linear medium “translates” the mid-IR signals to the NIR wavelength range, where a standard CCD camera can be used for the image acquisition. A lithium niobate (LN) crystal can for example be selected as the birefringent phase matched nonlinear medium for the upconversion process. Phase matched upconversion occurs from mixing of the monochromatic object light and the seed light. Scanning / variation of the phase match condition can be provided by having a non-linear crystal performing a tiny angular rotation (of approx. 1 degree) resulting in a large monochromatic field of view (FoV). The detector unit can be synchronized with the crystal rotation and an upconverted mid-IR 64 kpixels image can be acquired in only 2.5 ms thereby eliminating need for post-processing, i.e. direct detection can be provided.

When using monochromatic object light, a specific phase match condition of the non-linear medium corresponds to a specific part of the object being imaged, typically in the form of almost circular ring on the resulting upconvered image. Varying the phase match condition provides a number of these rings, typically in concentric fashion when scanning the phase match condition. The inventors have surprisingly realized that the image in each of these rings is non-blurred, i.e. the image part of the object imaged for a specific phase match condition is non-blurred, i.e. varying the phase match condition does not affect the resolution of the image. Hence, acquiring an image during variation of the phase match condition can directly provide a full image of the illuminated object without the need for image post-processing, i.e. direct detection is provided. As acquisition of one image over a range of phase match conditions can be provided on a micro-second scale, infrared video image direct detection can be provided by means of the presently disclosed approach.

A simple, versatile and fast mid-IR imaging system can thereby be provided, because imaging limitations imposed by the phase match condition of the nonlinear medium are circumvented by switching to monochromatic illumination light. Hyperspectrality can be provided by adjusting the wavelength of the monochromatic illumination light. The presently disclosed approach is generic in nature and constitutes a major simplification towards realizing video-frame-rate hyperspectral imaging. The presently disclosed system and method have the potential for fast and automated medical biopsy analysis based on the chemical fingerprint in the mid-IR range, potentially allowing for the use of endogenous chromophores for medical diagnostics, rather than using exogenous staining as is the golden standard today.

One example is breast cancer that is the most commonly diagnosed cancer amongst females in the USA and comes in second place as the most frequent cause of death from cancer after lung cancer. In 2017, around 41,000 women are expected to die from breast cancer in the USA [1]. In order to increase the survival rate, early diagnosis is important. In this context, the microcalcifications are the unique early marker for breast cancer detection.

The presently disclosed upconversion technique can be used to image microcalcifications at wavelengths close to 10 pm. The main technical effect of using the presently disclosed system and method in comparison with existing FTIR based systems (using focal plane arrays) is speed: FTIR systems use roughly 30 min to acquire a set of monochromatic images. The presently disclosed approach can provide a monochromatic image in 10 milliseconds. Hyperspectrality can be provided by wavelength tuning of the illumination light source.

The second method used nowadays for mid-IR biopsy screening is a raster scan approach using QCLs (Daylight solution). The raster scan, i.e. point by point scanning of the sample, is slow requiring substantial mechanical movements. This is in contrast to the presently disclosed approach that can obtain video frame rates.

Description of drawings

Fig- 1 shows an experimental setup for demonstrating the presently disclosed upconversion imaging wherein beams (object light + seed light) are spatially and temporally overlapping in the nonlinear crystal (lithium niobate) for efficient upconversion.

Figs. 2A-C show upconverted images of a USAF resolution target at 3.1 pm by varying the crystal rotation angle **(-4. 7°, -4.** 3°, **-4. 0°), figs. 2D-F** show the corresponding simulated images at the same angles.

Figs. 3A-I show various examples of upconverted images and the corresponding intensity profiles.

Figs 4A-C show upconverted image wheren rotating the crystal 1 degree, magnified version extract thereof and intensity profile along the stippled line in fig. 4B.

Figs. 5A-C illustrates the principle of applying nonlinear scan of the non-linear crystal.

Fig. 6A shows an experimental for setup for imaging of tissue samples and **figs. 6B-C** show the resulting images.

Detailed description of the invention

The monochromatic infrared object light used herein is typically provided by illuminating an object of interest, aka sample of interest, with monochromatic infrared illumination light, such as monochromatic infrared illumination light provided by at least one infrared illumination light source which can configured to provide monochromatic light. E.g. by means of a narrow linewidth light source, such as a laser, or by means of a broader line width light source and the application of a filter to obtain monochromatic light. Hence, both coherent and incoherent light sources can be used. Incoherent light sources may even be advantageous because speckles in the images can be avoided.

However, in a broad aspect of the present invention the illumination light source is not part of the claimed invention because the presently disclosed approach applies broadly to almost any kind of infrared object light. However, in further embodiments at least one illumination light source can be part of the claimed invention. Likewise for the seed light: In the broadest aspect of the present invention a seed light source is not part of the claimed invention because the presently disclosed approach applies broadly to almost any kind of infrared object light and seed light that can be used to upconvert the infrared object light. However, in further embodiments at least one seed light source can be part of the claimed invention. The seed light source may be a pump light source configured for pumping the illumination light source as exemplified herein.

The object of interest can be located in a plane and the monochromatic infrared object light can then be provided by transmitting monochromatic infrared illumination light through said plane. The wavelength of the monochromatic infrared object light is typically between 2 and 30 pm, more preferably between 2 and 20 pm, most preferably between 2 and 15 pm. The monochromatic infrared light and the seed light can be continuous wave (CW) light but the preferred choice is pulsed light. In case of a pulsed light setup the object light and the seed light must be synchronized, at least inside the non-linear medium in order for frequency upconversion to take place. I.e. in case of CW light, there is no naturally need for synchronization between object light and seed light. The bandwidth of the monochromatic object light is typically below 100 nm, more preferably below 50, even more preferably below 25, most preferably below 10 nm and typically between 4 and 6 nm or even sub nanometer/single-frequency light, i.e. monochromatic light.

The illumination light source may be an optical parametric oscillator, as exemplified herein, which is pumped by a pump light source which also functions as the seed light source. However, in order to reduce the size and the cost of the presently disclosed system, other infrared light sources can be used, e.g. one or more semiconductor lasers for emitting infrared light, such as quantum cascade lasers (QCL), which are very efficient low cost infrared light sources. A semiconductor laser will not need pumping, i.e. the seed laser and the illumination light source are independent. In a pulsed setup synchronization between the seed light and the object light can be provided by electronically triggered light sources. A further advantage of semiconductor lasers / QCLs is that hyperspectrality can be provided by wavelength tuning of the illumination light source. E.g. when using QCLs the wavelength tuning will be sub seconds for selecting discrete wavelengths.

In case of pulsed light and a pump light source for pumping the illumination light source, at least one delay line optical element may be provided for forming a fixed delay line configured to synchronize the light from illumination light source and light from the pump (seed) pulse such that the two can be synchronously mixed inside the non-linear medium.

In one embodiment the seed light source is a mode-locked pulsed laser, such as a mode-locked picosecond pulsed laser. Further, the seed light source may be a fiber laser, such as a Yb-fiber laser.

Controlled variation of the phase match condition inside the non-linear medium can be provided in various ways. For example the non-linear medium can be spaciously adjustable to vary the phase match condition by varying the trajectory of the mixed signal through the non-linear medium. The phase match condition can also be varied by varying the angle of incidence of the mixed signal relative to the non-linear medium thereby varying the trajectory through the non-linear medium.

In one embodiment the system is configured to periodically scan the phase match condition of the non-linear medium in synchronization with image integration in the detector unit, such that one period, or an integer number of periods, of phase match scanning corresponds to acquisition on one image in a sequence of images; a sequence of images that can correspond to a sequence of video images, i.e. video frame rate imaging, e.g. at least 10, 25, 50, 100 or even at least 400 frames per second.

In one embodiment the phase match condition is scanned by controlled rotation of the non-linear medium and/or of the incidence angle of the mixed signal. It will often be much simpler to rotate the non-linear medium relative to the optical axis of the mixed signal but in some case it can be a better (or the only) solution to scan the optical axis of the mixed signal relative to the non-linear medium

A large variation of the phase match condition, e.g. by means of a large rotation of a crystal, provides a larger field of view of the resulting image. However, the quality of the image may be worse for large angles and the frame rate of the image acquisition may be less because a larger physical movement is needed. Hence, the size of the variation of the phase match condition during acquisition of one image is a compromise between field of view, image quality and frame rate.

Often the required rotation is very small, hence controlled rotation is preferably provided with sub-degree resolution, such as 0.1 degree resolution or less than 0.1 degree resolution, stepwise or continuous rotation. The maximum controlled rotation of the incidence angle of the mixed signal relative to the non-linear medium (or vice versa) will typically be less than about 6 degrees, preferably less than or equal to 2 degrees, most preferably less than or equal to 1 degree.

In the example disclosed herein rotation of a non-linear crystal a mere 1 degree is implemented by mounting the crystal on a scanning unit in order to rotate the non-linear medium about the optical axis of the object light, in the example a Galvano-scanner (GVS) employing tangential phase matching is the scanning unit. This tiny crystal rotation increases the field-of-view (FoV) by a factor of approx. five compared to a fixed crystal angle, thereby increasing the number of pixels in the upconverted image by a factor of approx. 25.

In the preferred embodiment of the presently disclosed system and method a periodic scan of the phase match condition corresponds to one cycle of the maximum rotational variation of the non-linear medium relative to the incidence angle of the mixed signal. If the maximum rotation is 1 degree, one cycle may be the rotation from 0 to 1 degree, and the subsequent cycle can be the rotation from 1 to 0 degrees. Alternatively a period scan of the phase match conditions may correspond to an integer number of (rotational) cycles.

Actually the crystal can be scanned in an arbitrary / random fashion, e.g. including jumping between angular positions, without the resolution of the resulting upconverted image is degraded. However the image may then be over-exposed in certain rings, i.e.

certain parts of the image. Hence, it is preferred that the variation /scanning of the phase match condition of the non-linear medium during acquisition of each image, e.g. each image in a sequence of images, is adapted to the specific need in the specific situation. E.g. what is the intensity profile of the object light, which part or parts of the object is / are most interesting, etc.

In the preferred embodiment of the presently disclosed system and method image integration in the detector unit is provided during scanning of the phase match condition, preferably one cycle of a periodic scan of the phase match condition is integrated into one image in the detector unit, optionally an integer number of cycles are integrated into one image. This is an important aspect of obtaining large field-of-view (direct detection) infrared imaging because image post-processing can be avoided. As exemplified herein, the crystal rotation cycle time can be adjusted to match the camera integration time and an image with increased FoV is acquired directly without post-processing. This allows for video frame rate imaging. Monochromatic mid-IR upconversion imaging with a frame acquisition time of 2.5 ms is demonstrated in the example below, showing the potential to acquire up to 400 frames per second. The demonstrated spatial resolution is 35 pm within a 10 mm diameter FoV in the object plane, providing approx. 64 K spatially resolvable elements. The approach demonstrated in the example below is limited primarily by the lens optics, well-known from standard imaging configurations.

In one embodiment of the present disclosure an image acquisition time of less than 100 ms, preferably less than 50 ms, more preferably less than 25 ms, even more preferably less than 10 ms, yet even more preferably less than 5 ms, most preferably less than or equal to 2.5 ms, is provided. This may correspond to a frame rate of the image acquisition of at least 5 frames per second, preferably at least 10 frames per second, more preferably at least 25 frames per second, even more preferably at least 100 frames per second, yet even more preferably at least 200 frames per second, most preferably at least 400 frames per second.

The flexibility of the GVS even allows compensation of the intensity distribution of the seed light, which is Gaussian in the example herein with a pump light source. A nonlinear scan can be provided by adjusting the crystal rotation angle to provide a more uniform brightness in the upconverted image. Hence, scanning of the phase match condition can be provided with variable speed, e.g. angular speed of the rotation of the crystal angle, during one cycle of the scan in order to provide for a more uniform intensity profile over the full field-of-view. Preferably the speed of the scan is selected to be highest when the center of the detector is illuminated and slower towards illumination of the rim of the detector unit. The camera integration may be adjusted on the fly in correspondence herewith.

In another embodiment scanning of the phase match condition is stepwise such that the detector unit may acquire an image for each step of the periodic scan of the phase match condition.

In a further embodiment a first optical Fourier element for Fourier transforming the monochromatic infrared object light prior to mixing with the seed light and optionally a second optical Fourier element for Fourier transforming the upconverted object light onto the detector unit may be provided. This kind of optical Fourier transformation is one viable solution as also demonstrated in the example below.

A beam combiner can be provided for forming the s mixed signal, i.e. combining the seed light and object such that they can be mixed - synchronously mixed in case of pulsed light source(s).

At least one filtering optical element can be provided which is configured for blocking residual seed light and stray light after passage of the light through the nonlinear medium to prevent the residual and stray light from reaching the detector unit. Likewise at least one image focusing optical element, e.g. one or more lenses, may be provided which is configured to focus the upconverted object light onto the detector unit.

The diameter of the illumination light incident on the object of interest may be at least 2 mm, more preferably at least 5 mm, even more preferably at least 8 mm, most preferably about 10 mm. I.e. a rather large illumination spot may be possible if that is required, e.g. by the size of the object.

In the approach described above the entire object is illuminated but in order to increase the field-of-view, the phase match condition of the non-linear medium can be varied, i.e. in reality the entire object is not imaged concurrently because phase match condition scanning means that the field-of-view is scanned across the object. I.e. the object is illuminated by a lot of photons that never reach the detector, i.e. intensity of the illumination light is wasted. In a further embodiment of the invention the illumination light is focused onto the relevant part of the object of interest, i.e. for each small increment in time during image acquisition only the part of the object that is actually imaged in the detector unit is illuminated by illumination light.

I.e. during scanning of the phase match condition of the non-linear medium, the illumination light may correspondingly be directed and focused onto the subset of the object of interest that corresponds to the specific phase match condition. This may for example be provided by mean of MEMS (microelectromechanical) technology, e.g. by means of an optical assembly which can be configured for directing and focusing the monochromatic illumination light onto the subset of the object of interest that corresponds to the specific phase match condition. This optical assembly may comprise a plurality of MEMS optical elements for controlling and manipulating the monochromatic illumination light. In that regard it is noted that the optical assembly typically then must be synchronized with the phase match scanning and image integration in the detector unit.

Each of said subsets of the object of interest may correspond to a ring of illumination light on the object of interest and wherein a group of said subsets formed from one cycle of a scan of the phase match condition of the non-linear medium forms a set of concentric rings of illumination light on the object of interest, i.e. such that over one cycle the entire object of interest is illuminated. The result is this approach is that either imaging can be provided much faster, because more photons are incident on the relevant part of the object of interest, and/or the necessary intensity of the illumination light source can be reduced because the available photons from the light source can be focused to the relevant subset of the object, thereby reducing the power consumption and/or the cost of the illumination light source.

Examples

Two examples are included illustrating 1) the potential within fundamental band gas spectroscopy, and 2) fast IR monochromatic imaging of biopsies.

Experimental setup

An optical parametric oscillator (OPO) idler beam is used as the mid-IR illumination source. As shown in Figure 1, the mid-IR OPO is pumped at 1064 nm by a passively mode-locked picosecond (ps) Yb-fiber laser operating at a repetition rate of 81.1 MHz

(Fianium, FP1 060-20). The duration of the Yb-fiber laser pulses are 20.8 ps and the bandwidth is approx. 1 nm. The maximum available average power is 15 W out of which 10 W is used as pump for the OPO, while the remaining 5 W (attenuated to 1.5 W to avoid camera saturation) serves as a pump / seed field for the upconversion process, i.e. sum frequency generation (SFG). The synchronous upconversion pumping scheme incorporated here inherently locks the mid-IR OPO pulses and the pump laser pulses minimizing timing jitter at the ps scale. This feature is particularly feasible for synchronously pumped picosecond OPO's, in contrast to nanosecond pumped OPO's where the individual pulse builds up from parametric fluorescence introducing timing jitter in the ns range.

The high temporal stability allows operation of the upconversion setup passively, using a fixed delay line adjusted to synchronize the mid-IR OPO pulse and the pump pulse to coincide inside the nonlinear crystal [[7]]. Synchronous pumping is highly efficient since the high peak power pulses interact in perfect temporal synchronism, resulting in efficient upconversion.

A periodically poled $UNBO_3$ (PPLN) crystal is used as the nonlinear medium in the OPO, generating the signal and the idler beam. The PPLN crystal is operated at constant temperature. Depending on the preferred wavelength, either signal or idler beam is accessible for illumination. The signal wavelength can be tuned in the range of 1.43 to 1.98 pm with a bandwidth of approx. 1 nm. The idler beam correspondingly covers the range 2.3 to 4.1 pm with a bandwidth of 4 to 6 nm depending on the specific IR wavelength. The illumination bandwidth defines the spectral bandwidth of the monochromatic images shown later.

Fig. 1 shows a perspective illustrative view of the setup for the upconversion based imaging where the idler from a picosecond (ps) OPO is used as an illumination source and a synchronized ps 1064 nm laser source is used as a pump source. The beams are spatially and temporally overlapping in the nonlinear crystal (lithium niobate) for efficient upconversion. The phase matched condition is scanned by rotating the crystal in synchronism with the camera integration time. Lenses f_1 (50 mm) and f_2 (50 mm, 100 mm) are used at front and back focal plane of the 4f setup. Filters (shortpass 950, longpass 700) are used to block the residual pump/stray light.

The idler beam is used for illumination of the object. The idler beam diameter is approx. 10 mm (1/e^2 of Gaussian), which defines the FoV in the object plane. An average power of 750-900 mW (depending on the wavelength) is available in a near Gaussian intensity distribution. The pump beam for upconversion, i.e. the 1064 nm laser, has a diameter of approx. 4 mm (1/e^2 of Gaussian) inside the nonlinear material. A birefringent phase matched lithium niobate (LN) crystal with a cut angle of 48° with respect to the c-axis acts as the nonlinear medium for the upconversion. The large transverse dimension of bulk LN crystals compared to its PPLN counterpart, allows the use of a large pump beam diameter promoting high spatial resolution of the upconverted images (the pump beam here acts as a soft Gaussian aperture) [[8]]. It is further noticed that bulk crystals constitute a major class of nonlinear crystals available for mid-IR applications beyond 4.5 pm, thus the bulk LN choice supports future applications in the 5 to 15 pm range, or even up to 20 pm and above.

The upconversion setup is implemented as a 4f configuration where the upconversion process takes place in the Fourier plane relative to the object. A first lens / $_l$ (= 50 mm) Fourier transforms the two-dimensional mid-IR object field to the center of the LN crystal where synchronous upconversion to the near infrared (NIR) takes place. A second lens f_2 Fourier transforms the upconverted NIR signal to form an image at the CCD camera chip [[3]-[5],[7]], of. fig. 1. A Si-based CCD camera (Andor Luca S) is used for the image acquisition. Filters (short pass 950, long pass 700) are inserted to block the residual pump and stray light from reaching the camera.

Different arrangements exist for the frequency upconversion process. Using simple collinear interaction in a birefringent phase matched material typically leads to a narrow and often highly elliptical field of view [[9]]. However, choosing an appropriate off-set angle between the mid-IR signal and the pump beam, leads to a larger and more circular FoV. This phase match condition is commonly referred to as tangential phase matching [[9]]. For a specific monochromatic IR signal and corresponding crystal angle, a uniquely defined cone of mid-IR light is optimally phase matched, corresponding to a ring pattern when Fourier transformed to the image plane. Changing the crystal angle successively, a set of concentric phase matched rings will appear, each new ring adding to the FoV.

Fig. 2 shows experimentally as well as theoretically the upconversion imaging process. A USAF resolution target is inserted in the object plane to demonstrate the spatial properties of the imaging system. Figs. 2A-C show measured upconverted images for different crystal rotation angles, i.e. USAF resolution target at 3.1 pm by varying the crystal rotation angle (-4. 7°, -4. 3°, -4. 0°). Figs. 2D-F show their simulated counter parts. The two sets of figures are seen to match very well.

To increase FoV in a monochromatic image, the phase match condition can be tuned to upconvert different sections (rings) of the object plane as seen in fig. 2 and then combined to form an image with large FoV. Angular tuning of the crystal is a particularly efficient approach since a tiny crystal angle rotation can lead to large change in the phase match mid-IR angles. Several approaches to increase FoV have been proposed in recent years, however, these are complicated to implement, of limited generality, or slow in nature [[2]-[5],[1 0]]. A superposition of partially overlapping upconverted images (or ring patterns) at the CCD camera chip while scanning the phase match condition preserves the image quality producing a significantly increased FoV.

In this example, the need for post-processing of the images has been eliminated by introducing a GVS (Thorlabs GVS01 1) and image integration by the CCD camera. The nonlinear crystal is mounted on a GVS for automated and controlled rotation of the crystal. An analog/digital signal generator (USB-621 1 National Instruments) is used to generate a synchronized voltage signal for the GVS and the CCD camera respectively using an external trigger signal. A LabVIEW program then controls the GVS voltage setting to generate synchronous scanning of the GVS and the trigger signal of the CCD camera. By integrating all the upconverted sub-images while scanning the crystal angle in a predefined range, a large FoV is obtained without the need for post-processing. In practical terms, the GVS sweep average out the *Sine* term from the phase match condition point by point. In particular, a nonlinear scan pattern can compensate for the Gaussian nature of the illumination source, thus generating a flat response over the full FoV, i.e. producing an isoplanatic imaging system.

In the following, the basic properties of the upconversion set-up are investigated. Figs. 3A-B show measured upconverted images where fig. 3A is single frame acquisition i.e. tangential phase-matching and fig. 3B is the post-processed upconverted image composed of super imposed individual frames captured at crystal rotation angles ranging from -4.7° to -3.7° in steps of 0.1° with respect to the c-axis and stitching the images together. The ratio between the diameters of the two images in fig. 3A and fig.

3B is a direct measure of the increase in FoV. The camera integration time for each frame is 0.47 ms, limited by the minimum exposure time setting of the camera. Even then, the pump source had to be attenuated to keep the camera from saturation, highlighting the advantage of synchronous upconversion for high quantum efficiency.

Fig. 3C shows the individual intensity profiles along the x-axis (illustrated with dotted line in fig. 3B) while the topmost graph represents the sum of the intensity profiles. The intensity profile of the upconverted image is near Gaussian reflecting the intensity profile of the OPO idler beam.

Fig. 3D shows the measured beam profile of the idler illumination source using a standard mid-IR camera. Fig. 3E is the acquired image using the GVS doing a continuous linear scan of the crystal angles and integrating with the CCD camera with an integration time of 2.5 ms. Fig. 3F shows a comparison of the intensity profiles measured with the GVS scanner using post-processing with stepwise scanning of the crystal angle and single frame acquisition, using the proposed continuous GVS scanning and the direct detection with the mid-IR camera. The images are very similar validating the use of continuous GVS scanning as a practical method to increase the FoV.

Fig. 3G-I show the theoretically calculated images corresponding to fig. 3A-C, using the measured mid-IR beam profile as input.

Fig. 4C shows the intensity profile along the stippled line in fig. 4B and ellipse to the right in the graph highlights the smallest features.

To experimentally determine the spatial resolution, a standard resolution target USAF target (Edmund optics clear path resolution target) is placed in the object plane (of. fig. 1). Fig. 4A shows an upconverted image of the resolution target at 3.1 pm rotating the crystal from -4. 7° to -3. 7° with respect to c-axis using GVS for automatized acquisition, i.e. crystal rotation synchronous to camera integration time, camera integration time spent on each frame is 2.5 ms. Fig. 4B shows the magnified version of the smallest features of the resolution target, i.e. square box in fig. 4A, f_2 was changed from 50 mm to 100 mm focal length for magnification. In fig. 4B the smallest feature of the resolution target that can be resolved is seen, i.e. approx. 35 pm (14 lines/mm). The camera has a pixel size of 10x1 0 pm^2 whereas the upconverted spatial features on the camera are smaller (i.e. ~8 pm) due to the demagnification imposed by the upconversion process. Therefore, the lens f_2 was changed from 50 mm in fig. 4A to 100 mm in figure 4B.

With a FoV of 10 mm in diameter and a resolution of 35 pm the number of resolvable elements corresponds to approx. 64 K. Calculation of the resolution using the point spread function yields a resolution of 34 pm hinting only an insignificant degradation in the actual upconverted image quality. The reason may be lens aberrations or the uncertainty of the actual pump beam diameter used, more than the upconversion process itself. I.e. issues that can be resolved by careful design of the optical elements.

The images shown so far all have a Gaussian intensity profile imposed by the mid-IR illumination source itself. To obtain a more homogeneous (top-hat) intensity profile over the full FoV, the angle of the nonlinear crystal can be scanned in a nonlinear fashion, such that the GVS rotates slower close to rim of the image compared to the center where the mid-IR intensity is highest. Fig. 5A shows the trend of such a nonlinear scan, i.e. a linear scan and the nonlinear scan used to produce the top hat like intensity profile. Fig. 5B shows the resulting upconverted image with a blank target at 3.1 pm when the GVS implemented the nonlinear scan. The exposure time is varied as^ relative to the angle for the center part of the image. Fig. 5C shows the intensity profile along the y-axis of the image in fig. 5B using nonlinear scanning, i.e. the lower curve. Compared to that of a linear scan (uppermost curve) a more top-hat like intensity profile is indeed seen. However, due to a slight asymmetry in the IR beam the full potential was not realized here, see fig. 3D.

Example 1

To illustrate video frame-rate upconversion imaging, butane was sprayed from a gas lighter in the object plane. By tuning the hyperspectral upconversion camera to match the absorption line of butane at 3.37 pm, a narrow band image was recorded. An image sequence was recorded while spraying butane gas in the object plane in front of the resolution target, but videos can unfortunately not be illustrated herein. With a 2.5 ms exposure time, the imaging system can acquire 400 frames per second, but in this example limited to 40 Hz readout time of the NIR camera.

Example 2

A further example of the applicability of the presently disclosed system and method is illustrated in Fig. 6, where the mid-IR illumination beam is scaled by lenses to match the size of a medical biopsy, i.e. 2 mm in diameter. The beam is then transmitted through the tissue sample, magnified to the 10 mm diameter used in the previous examples. This is then used as the object beam for the upconversion imaging system. Measuring two images, one with and one without the tissue samples allow for a pixel by pixel calculation of the transmission through the sample at the illumination wavelength, in the example at 3.34 pm. In this example the spatial resolution in the tissue sample plan is approx. 9 pm, taking into account the scaling systems introduced in fig. 6A.

Fig. 6A shows the magnification setup for the imaging of the tissue sample to resolve the smaller features of the sample. The original size of the beam coming from OPO is 10 mm, which is reduced to 2 mm, using a pair of lenses: f_1 = 250 mm, f_2 = 50 mm. This 2 mm beam illuminates the tissue sample, where the size of one sample is roughly 2 mm. The sample shown in the setup contains several biopsy samples mounted on a 1 mm thick CaF_2 substrate. After passing through the sample, the beam is magnified again by 5 times, using a second pair of lens: f_3 = 50 mm and f_4 = 250 mm. This magnified beam is then used as the object in the upconversion imaging system, as shown in fig. 1. Fig 6B shows the image of the tissue sample acquired using upconversion at 3.34 pm wavelength, whereas fig. 6C shows the corresponding image acquired using FTIR

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Items

1. A system for (direct) detection of infrared object light, the system comprising
   - an non-linear medium, such as a non-linear crystal, configured for
     - receiving 1) monochromatic infrared object light, and 2) seed light, and
     - mixing, e.g. synchronously, the monochromatic infrared object light, and the seed light for phase matched frequency upconversion of the monochromatic infrared object light inside the non-linear medium, and
   - a detector unit, such as a CCD, for imaging, e.g. video imaging, the upconverted object light,

   wherein the system is configured to vary the phase match condition of the non-linear medium during image acquisition in the detector unit such that acquisition of one image in a sequence of (video) images corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

2. The system according to item 1, wherein the non-linear medium is a crystal, such as a lithium niobate (LN) crystal.

3. The system according to any of the preceding items, wherein the wavelength of the monochromatic infrared object light is between 2 and 30 pm, more preferably between 2 and 20 pm, most preferably between 2 and 15 pm.

4. The system according to any of the preceding items, wherein the monochromatic infrared object light is provided by illuminating an object of interest with monochromatic infrared illumination light, such as monochromatic infrared illumination light provided by a monochromatic infrared illumination light source.

5. The system according to any of the preceding items, wherein the object of interest is located in a plane and wherein monochromatic infrared object light is provided by transmitting monochromatic infrared illumination light through said plane.

6. The system according to any of the preceding items, wherein the non-linear medium is spaciously adjustable to vary the phase match condition by varying the trajectory of the mixed signal through the non-linear medium.

7. The system according to any of the preceding items, wherein the phase match condition is varied by varying the angle of incidence of the mixed signal relative to the non-linear medium thereby varying the trajectory through the non-linear medium.

8. The system according to any of the preceding items, wherein the phase match condition is varied by controlled rotation of the non-linear medium and/or of the incidence angle of the mixed signal.

9. The system according to any of the preceding items 8, configured such that controlled rotation is provided with sub-degree resolution, such as 0.1 degree

resolution or less than 0.1 degree resolution.

10. The system according to any of the preceding items 8-9, configured such that the maximum controlled rotation of the incidence angle of the mixed signal relative to the non-linear medium relative is less than about 3 degrees, preferably less than or equal to 2 degrees, most preferably less than or equal to 1 degree.

11. The system according to any of the preceding items, wherein the system is configured to periodically scan the phase match condition of the non-linear medium in synchronization with image integration in the detector unit, such that one period, or an integer number of periods, of phase match scanning corresponds to acquisition on one image in a sequence of images.

12. The system according to any of the preceding items 11, wherein one period of phase match scanning corresponds to the maximum rotational variation of the of the incidence angle of the mixed signal relative to the non-linear medium.

13. The system according to any of the preceding items, comprising a scanning unit for rotation of the non-linear medium about the optical axis of the object light.

14. The system according to any of the preceding items 13, wherein the scanning unit is a Galvano-scanner.

15. The system according to any of the preceding items, wherein the monochromatic infrared light and the seed light are pulsed light or CW light.

16. The system according to any of the preceding items, comprising an illumination light source for illuminating an object of interest to provide the monochromatic infrared object light.

17. The system according to item 16, wherein the illumination light source is an optical parametric oscillator or a quantum cascade laser.

18. The system according to any of items 16-1 7, wherein the illumination light source is a coherent light source or an incoherent light source.

19. The system according to any of the preceding items, comprising a seed light source for providing the seed light.

20. The system according to any of the preceding items 19, wherein the seed light source is a pump light source configured for pumping the illumination light source.

21. The system according to any of the preceding items 20, comprising at least one optical element for forming a fixed delay line configured to synchronize the light from the illumination light source and light from the pump pulse.

22. The system according to any of the preceding items 19-21 , wherein the seed light source is a mode-locked pulsed laser, such as a mode-locked picosecond pulsed laser.

23. The system according to any of the preceding items 19-22, wherein the seed light source is a fiber laser, such as a Yb-fiber laser.

24. The system according to any of the preceding items, comprising a first optical Fourier element for Fourier transforming the monochromatic infrared object light prior to mixing with the seed light and a second optical Fourier element for Fourier transforming the upconverted object light onto the detector unit.

25. The system according to any of the preceding items, comprising a beam combiner for forming the mixed signal.

26. The system according to any of the preceding items, comprising at least one optical element configured for blocking residual seed light and stray light after passage of the mixed light through the nonlinear medium to prevent the residual and stray light from reaching the detector unit.

27. The system according to any of the preceding items, comprising at least one optical element configured to focus the upconverted object light onto the detector unit.

28. The system according to any of the preceding items, configured such that one cycle of a periodic scan of the phase match condition is integrated into one image in the detector unit, optionally an integer number of cycles are integrated into one image.

29. The system according to any of the preceding items, configured such that image integration in the detector unit is provided during scanning of the phase match condition.

30. The system according to any of the preceding items 28-29, configured such that variation of the phase match condition is provided with variable speed during acquisition of one image.

31. The system according to item 30, wherein the variation of the phase match condition is a scan and wherein the speed of the scan is highest when the center of the detector is illuminated and slower towards illumination of the rim of the detector unit.

32. The system according to any of the preceding items, configured to have an image acquisition time of less than 100 ms, preferably less than 50 ms, more preferably less than 25 ms, even more preferably less than 10 ms, yet even more preferably less than 5 ms, most preferably less than or equal to 2.5 ms, of each image in a sequence of images acquired in the detector unit.

33. The system according to any of the preceding items, configured such that scanning of the phase match condition is stepwise and such that optionally the detector unit acquires an image for each step of the periodic scan of the phase match condition.

34. The system according to any of the preceding items, wherein the diameter of the illumination light incident on the object of interest is at least 2 mm, more

preferably at least 5 mm, even more preferably at least 8 mm, most preferably about 10 mm.

35. The system according to any of the preceding items, configured such that during variation of the phase match condition of the non-linear medium, the illumination light is correspondingly directed and focused onto the subset of the object of interest that corresponds to the specific phase match condition.

36. The system according to 35, comprising an optical assembly configured for directing and focusing the monochromatic illumination light onto the subset of the object of interest that corresponds to the specific phase match condition.

37. The system according to any of the preceding items 36, wherein said optical assembly comprises a plurality of MEMS optical element for controlling the monochromatic illumination light.

38. The system according to any of the preceding items 35-37, wherein each of said subsets of the object of interest corresponds to a ring of illumination light on the object of interest and wherein a group of said subsets formed from one cycle of a variation of the phase match condition of the non-linear medium forms a set of concentric rings of illumination light on the object of interest.

39. A method for increased field-of-view direct detection of infrared object light, comprising the steps of

- mixing monochromatic infrared object light with seed light in a non-linear medium, such as a crystal, thereby frequency upconverting the monochromatic infrared object light by means of phase matching in the non-linear medium,
- varying the phase match condition of the non-linear medium to increase the field of view of the upconverted object light, and
- imaging the upconverted object light, e.g. by means of a CCD camera, such that acquisition of one image in a sequence of images corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

40. The method according to item 39, carried out by means of the system according to any of items 1-38

Claims

1. A system for detection of infrared object light, the system comprising
   - an non-linear medium, such as a non-linear crystal, configured for
     - receiving 1) monochromatic infrared object light, and 2) seed light, and
     - mixing the monochromatic infrared object light, and the seed light for phase matched frequency upconversion of the monochromatic infrared object light inside the non-linear medium, and
   - a detector unit, such as a CCD, for imaging the upconverted object light,

   wherein the system is configured to vary the phase match condition of the non-linear medium during image acquisition in the detector unit such that acquisition of one image in a sequence of images corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

2. The system according to claim 1, wherein the non-linear medium is a crystal.

3. The system according to any of the preceding claims, wherein the non-linear medium is a lithium niobate (LN) crystal.

4. The system according to any of the preceding claims, wherein the wavelength of the monochromatic infrared object light is between 2 and 20 pm.

5. The system according to any of the preceding claims, wherein the phase match condition is varied by varying the angle of incidence of the mixed signal relative to the non-linear medium thereby varying the trajectory through the non-linear medium.

6. The system according to any of the preceding claims, wherein the system is configured to periodically scan the phase match condition of the non-linear medium in synchronization with image integration in the detector unit, such that one period, or an integer number of periods, of phase match scanning corresponds to acquisition on one image in a sequence of images.

7. The system according to any of the preceding claims 6, wherein one period of phase match scanning corresponds to the maximum rotational variation of the

of the incidence angle of the mixed signal relative to the non-linear medium.

8. The system according to any of the preceding claims, comprising a scanning unitfor rotation of the non-linear medium about the optical axis of the object light for varying the phase match condition of the non-linear medium.

9. The system according to claims 8, wherein the scanning unit is a Galvano-scanner.

10. The system according to any of the preceding claims, configured such that one cycle of a periodic scan of the phase match condition is integrated into one image in the detector unit, optionally an integer number of cycles are integrated into one image.

11. The system according to any of the preceding claims, configured such that variation of the phase match condition is provided with variable speed during acquisition of one image to compensate for intensity distribution in the seed light.

12. The system according to claim 11, wherein the variation of the phase match condition is a scan and wherein the speed of the scan is highest when the center of the detector is illuminated and slower towards illumination of the rim of the detector unit.

13. The system according to any of the preceding claims, configured to have an image acquisition time of less than 10 ms of each image in a sequence of images acquired in the detector unit.

14. The system according to any of the preceding claims, configured such that during variation of the phase match condition of the non-linear medium, the illumination light is correspondingly directed and focused onto the subset of the object of interest that corresponds to the specific phase match condition.

15. The system according to 14, comprising an optical assembly configured for directing and focusing the monochromatic illumination light onto the subset of

the object of interest that corresponds to the specific phase match condition.

16. The system according to any of the preceding claims 15, wherein said optical assembly comprises a plurality of MEMS optical element for controlling the monochromatic illumination light.

17. The system according to any of the preceding claims 14-16, wherein each of said subsets of the object of interest corresponds to a ring of illumination light on the object of interest and wherein a group of said subsets formed from one cycle of a variation of the phase match condition of the non-linear medium forms a set of concentric rings of illumination light on the object of interest.

18. A method for increased field-of-view detection of infrared object light, comprising the steps of
   - mixing monochromatic infrared object light with seed light in a non-linear medium, such as a crystal, thereby frequency upconverting the monochromatic infrared object light by means of phase matching in the non-linear medium,
   - varying the phase match condition of the non-linear medium to increase the field of view of the upconverted object light, and
   - imaging the upconverted object light, e.g. by means of a CCD camera, such that acquisition of one image in a sequence of images corresponds to image integration over a plurality of phase match conditions of the non-linear medium.

19. The method according to claim 18, carried out by means of the system according to any of claim 1-17.

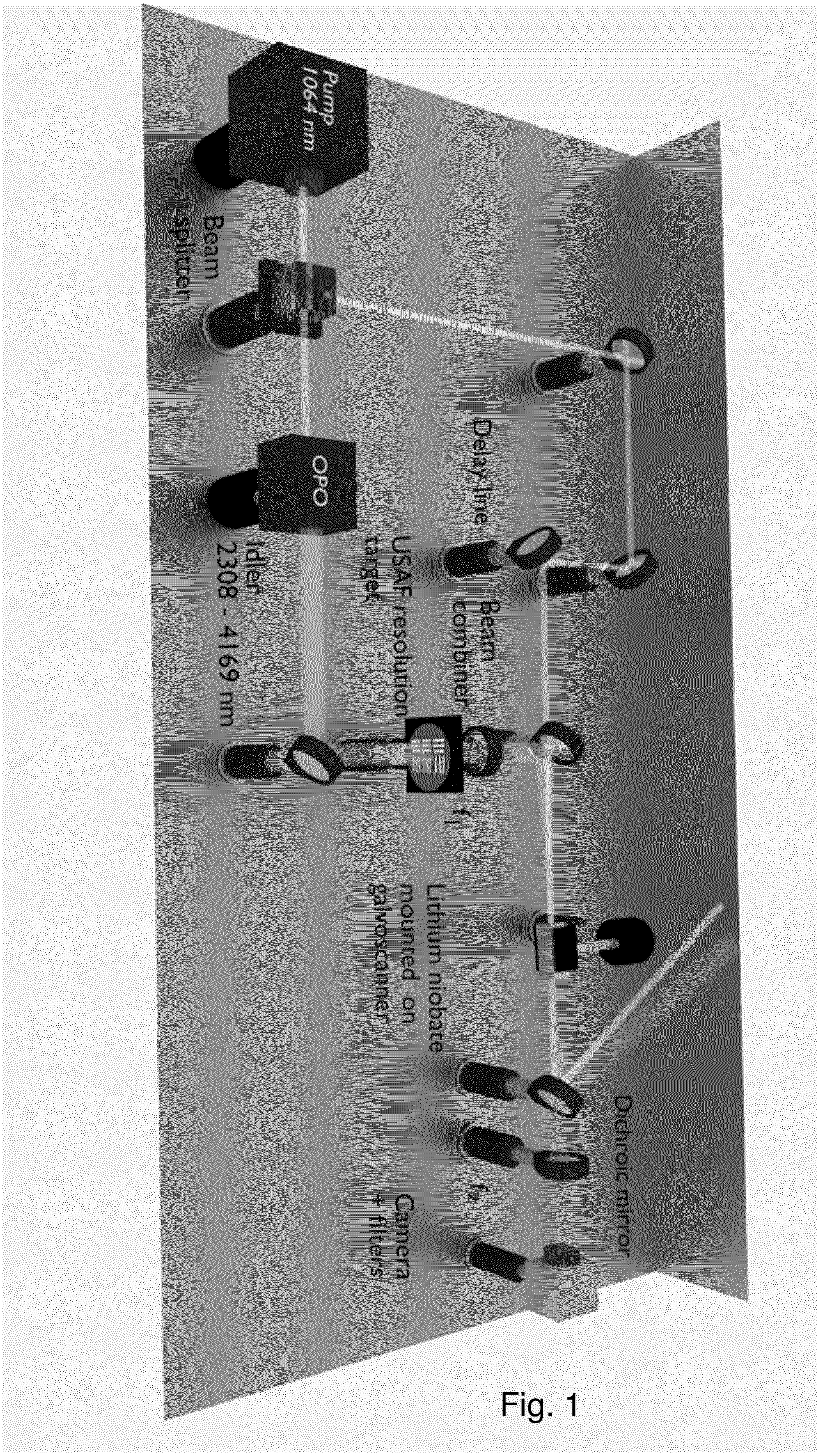
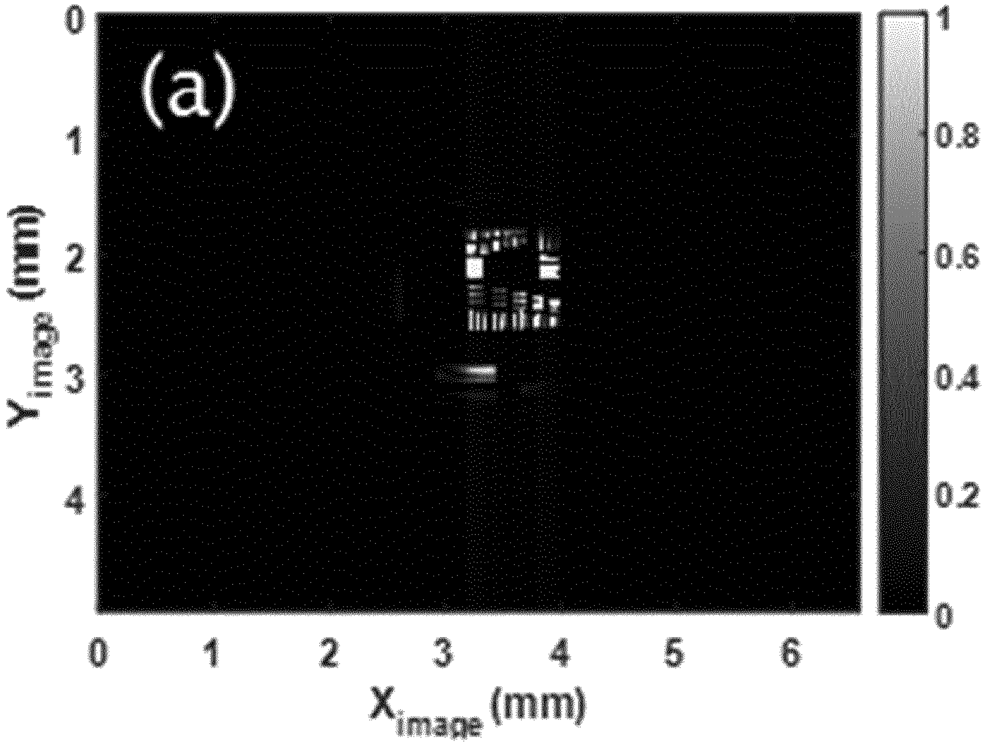

Pump
1064 nm
Beam
splitter
OPO
Idler
2308 - 4169 nm
Delay line
USAF resolution
target
Beam
combiner
f_1
Lithium niobate
mounted on
galvoscanner
Dichroic mirror
f_2
Camera
+ filters

Fig. 1


(a)
Y_image (mm)
X_image (mm)
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8

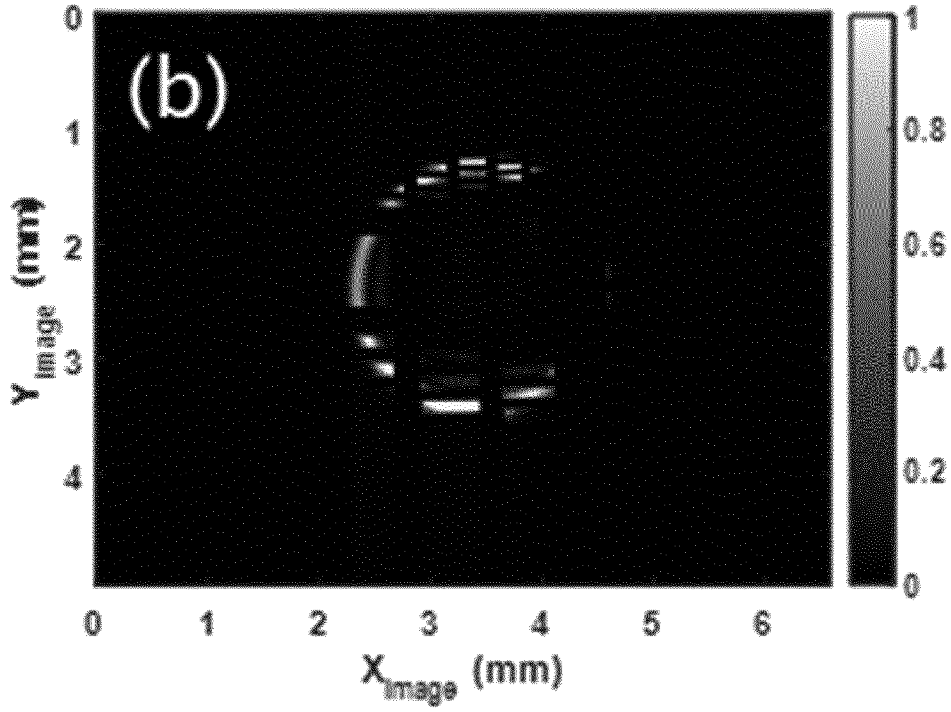

(b)
Y_image (mm)
X_image (mm)
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8

Fig. 2A-B

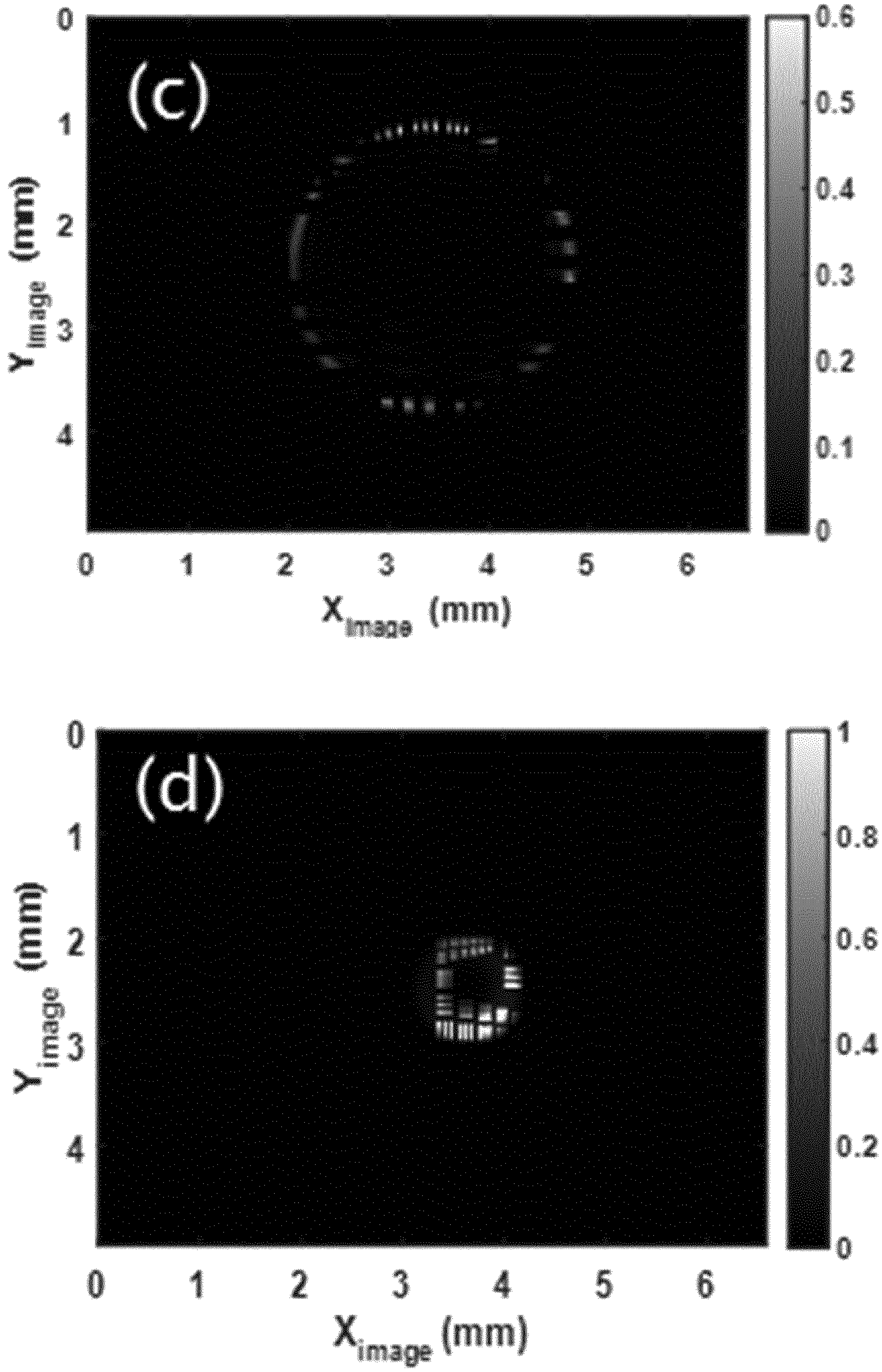

(c)
0
1
2
3
4
Y_{image} (mm)
0
1
2
3
4
5
6
X_{image} (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
(d)
0
1
2
3
4
Y_{image} (mm)
0
1
2
3
4
5
6
X_{image} (mm)
1
0.8
0.6
0.4
0.2
0

Fig. 2C-D

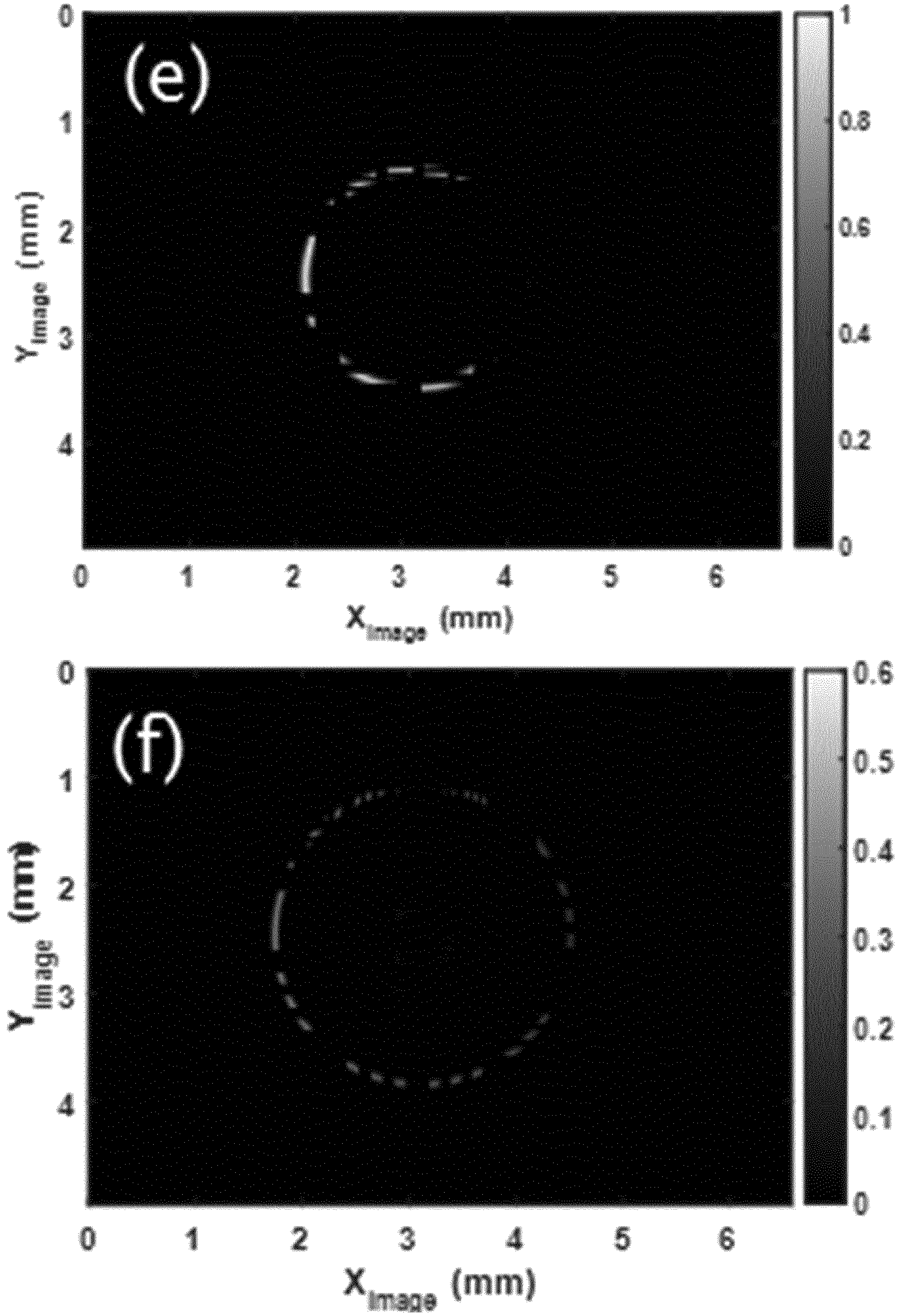

(e)
0
1
2
3
4
0
1
2
3
4
5
6
X_{image} (mm)
Y_{image} (mm)
1
0.8
0.6
0.4
0.2
0
(f)
0
1
2
3
4
0
1
2
3
4
5
6
X_{image} (mm)
Y_{image} (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0

Fig. 2E-F

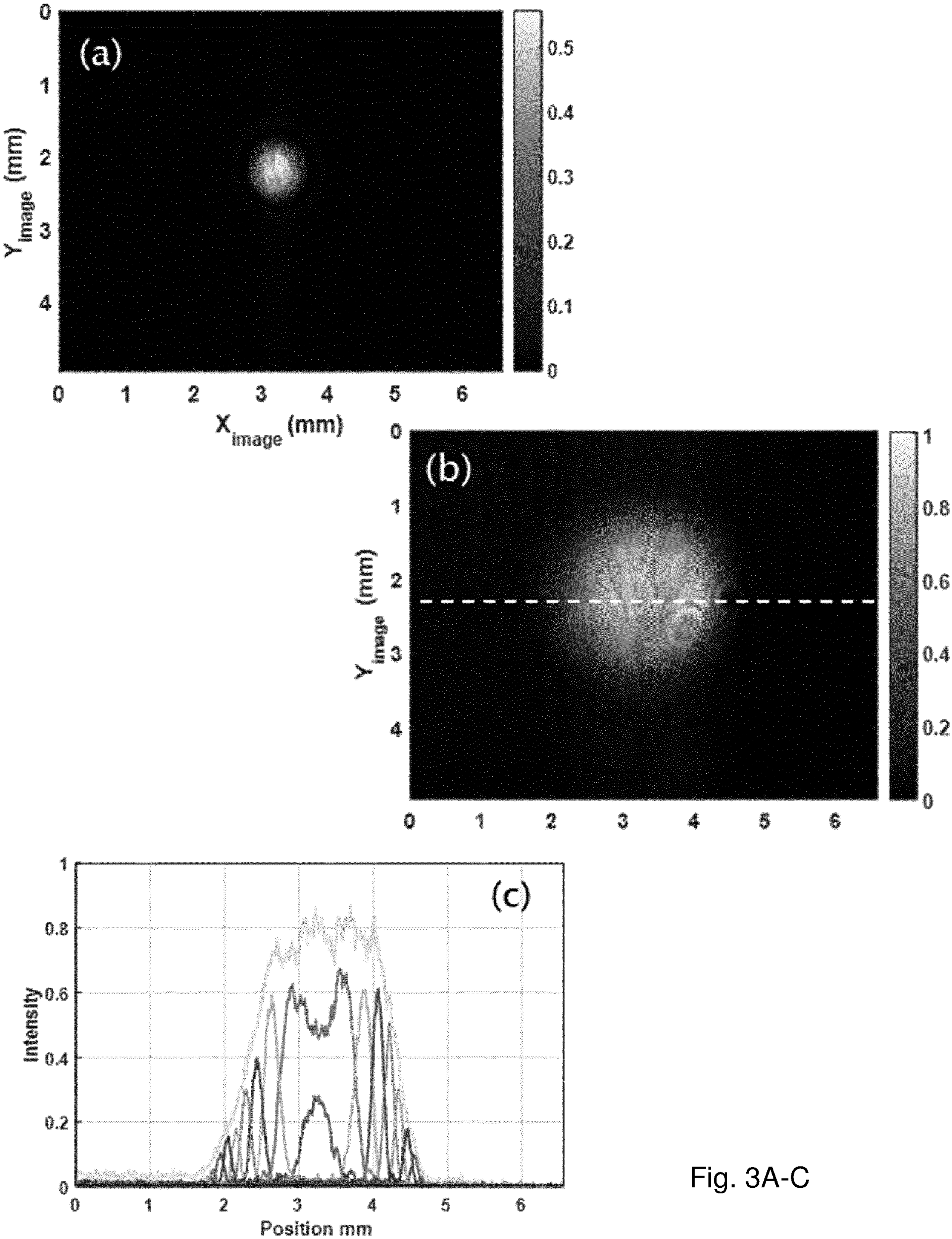

(a)
Y_image (mm)
X_image (mm)
0
1
2
3
4
5
6
0.5
0.4
0.3
0.2
0.1
(b)
0.8
0.6
(c)
Intensity
Position mm

Fig. 3A-C

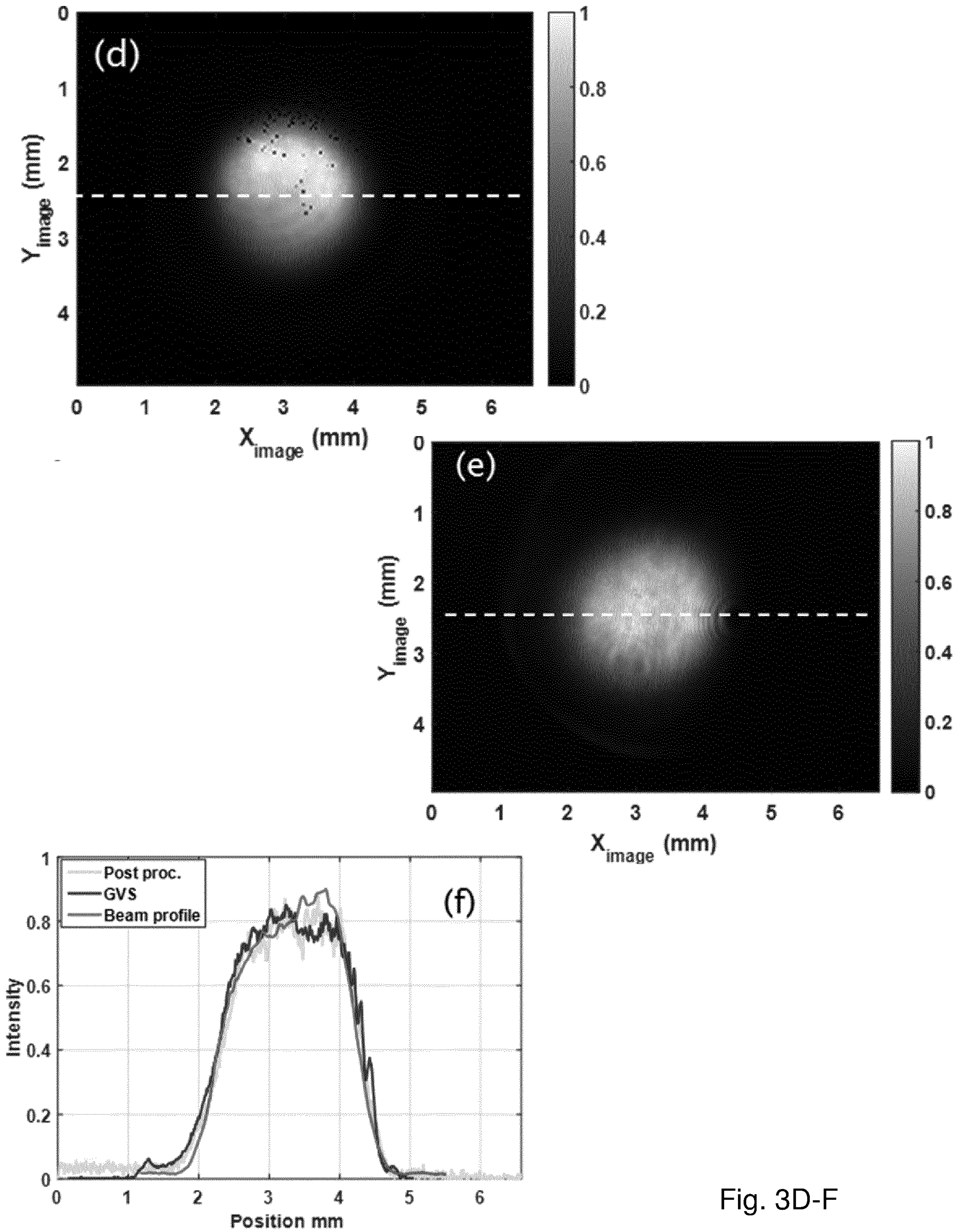
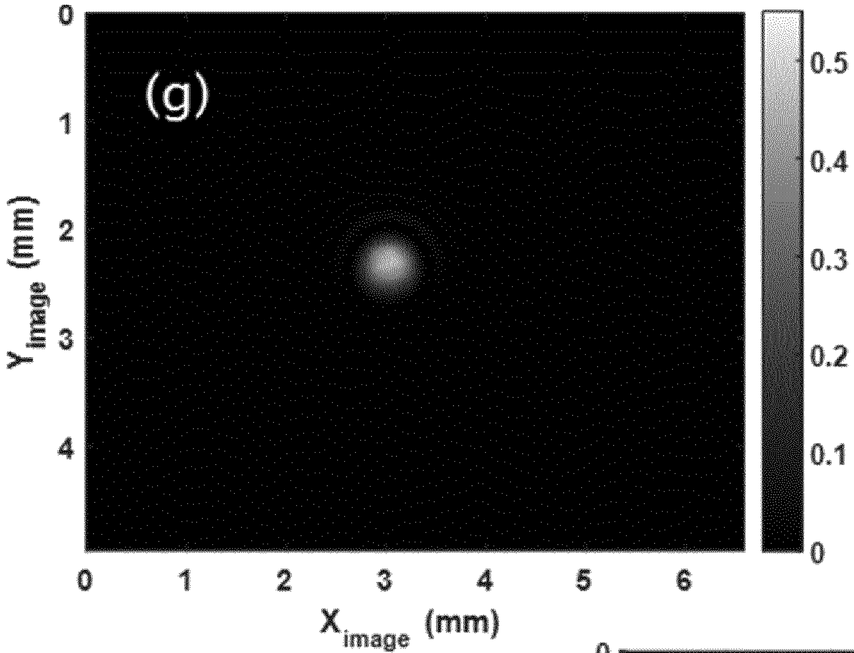
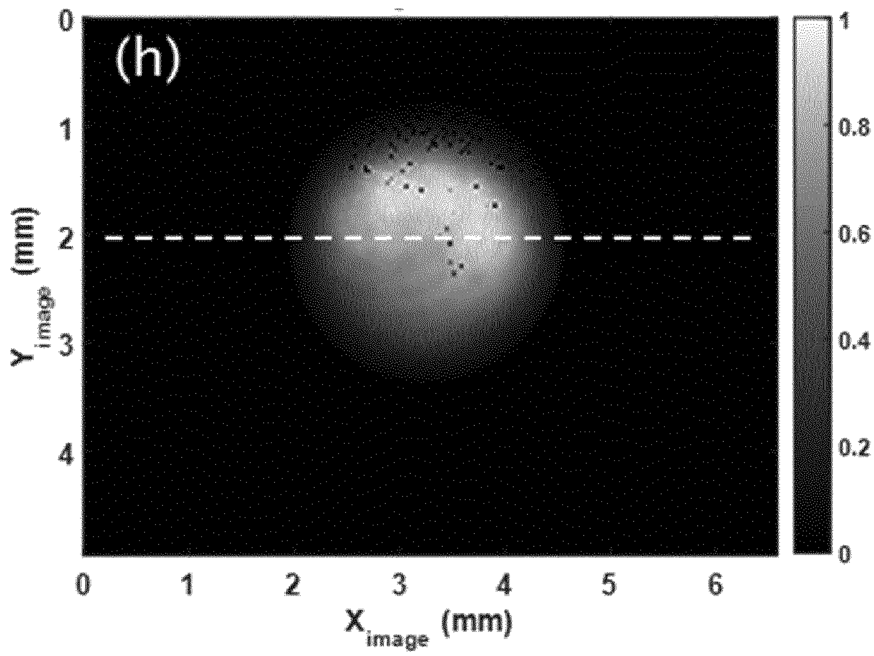

(d)
Y_{image} (mm)
X_{image} (mm)
(e)
Y_{image} (mm)
X_{image} (mm)
Post proc.
GVS
Beam profile
(f)
Intensity
Position mm

Fig. 3D-F


(g)
Yimage (mm)
Ximage (mm)
0 1 2 3 4
0 1 2 3 4 5 6
0 0.1 0.2 0.3 0.4 0.5


(h)
Yimage (mm)
Ximage (mm)
0 1 2 3 4
0 1 2 3 4 5 6
0 0.2 0.4 0.6 0.8 1

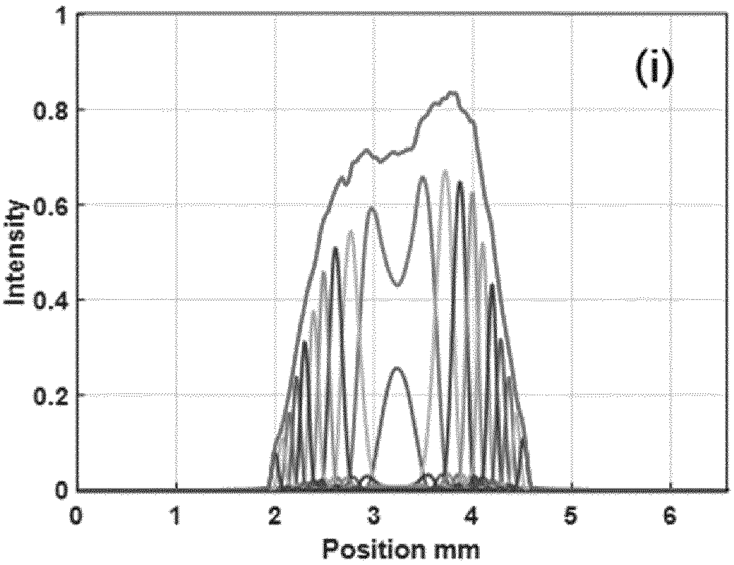

(i)
Intensity
Position mm
0 0.2 0.4 0.6 0.8 1
0 1 2 3 4 5 6

Fig. 3G-I

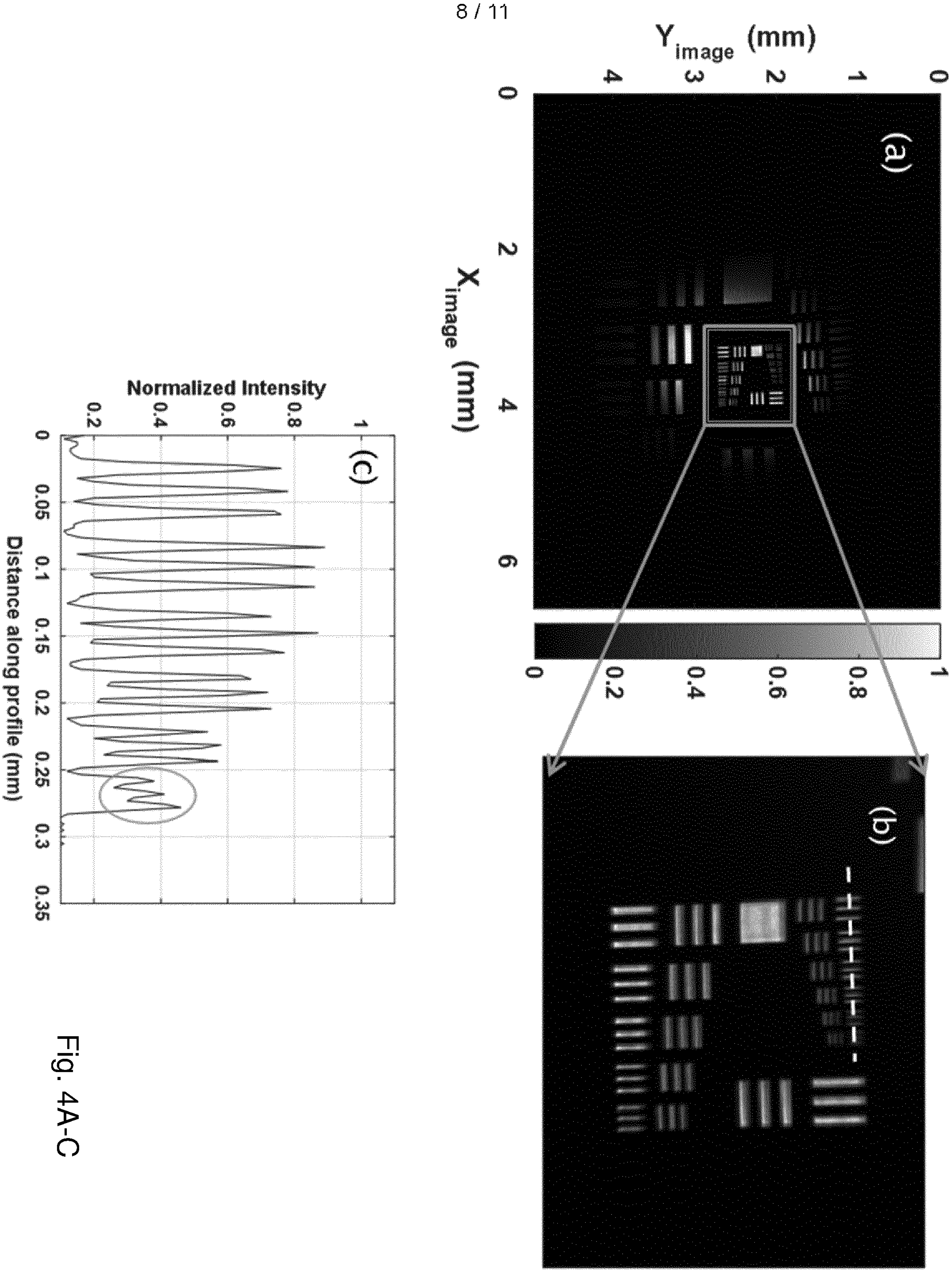

(a)
(b)
(c)
Y image (mm)
X image (mm)
Normalized Intensity
Distance along profile (mm)

Fig. 4A-C

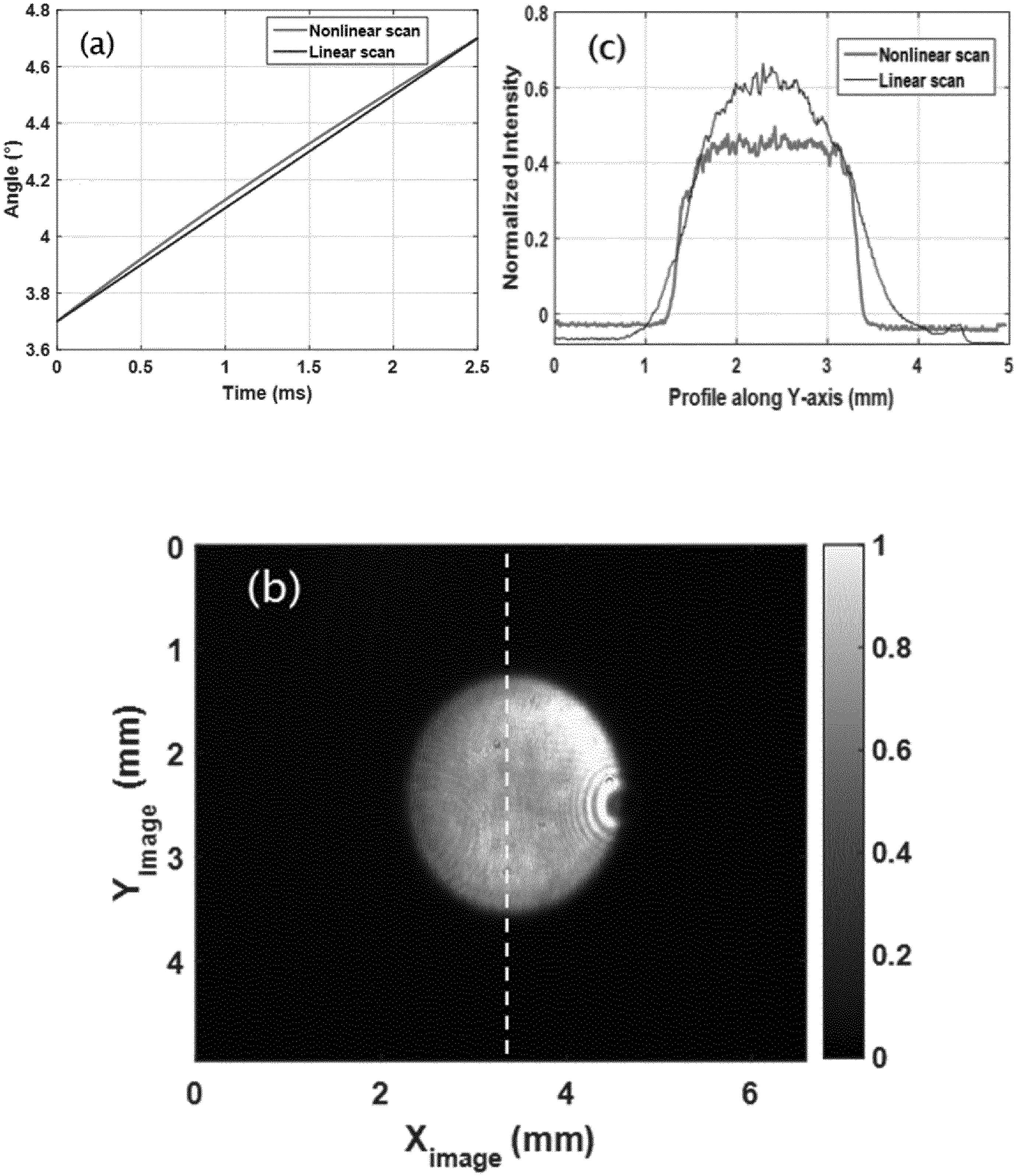

(a)
Nonlinear scan
Linear scan
Angle (°)
Time (ms)
4.8
4.6
4.4
4.2
4
3.8
3.6
0
0.5
1
1.5
2
2.5
(c)
Nonlinear scan
Linear scan
Normalized Intensity
Profile along Y-axis (mm)
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
(b)
Y Image (mm)
X image (mm)
0
1
2
3
4
0
2
4
6
1
0.8
0.6
0.4
0.2
0

Fig. 5A-C

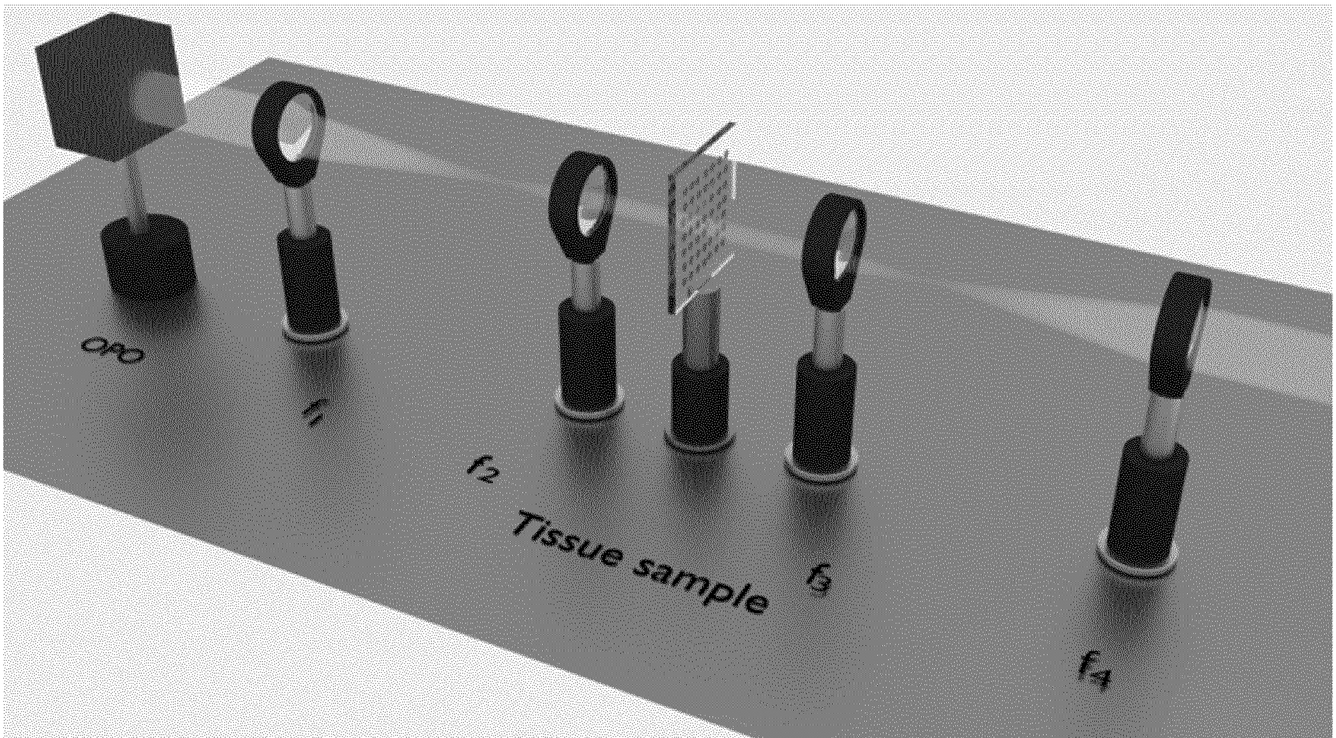


Fig. 6A

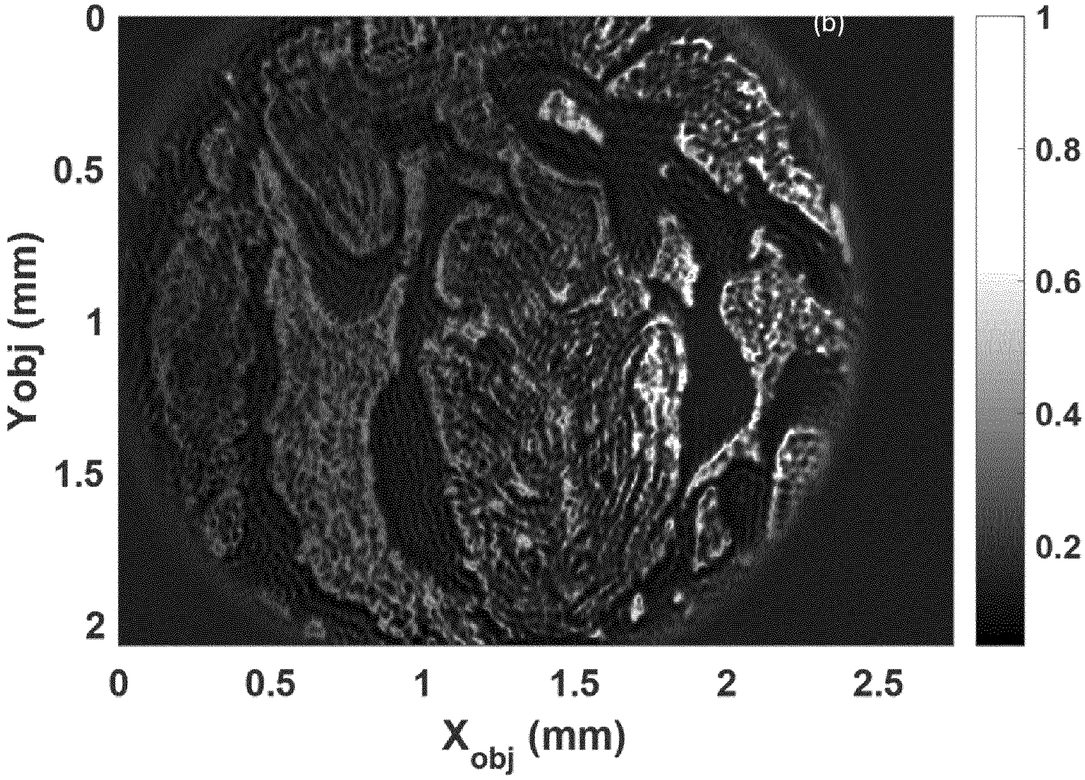


Fig. 6B

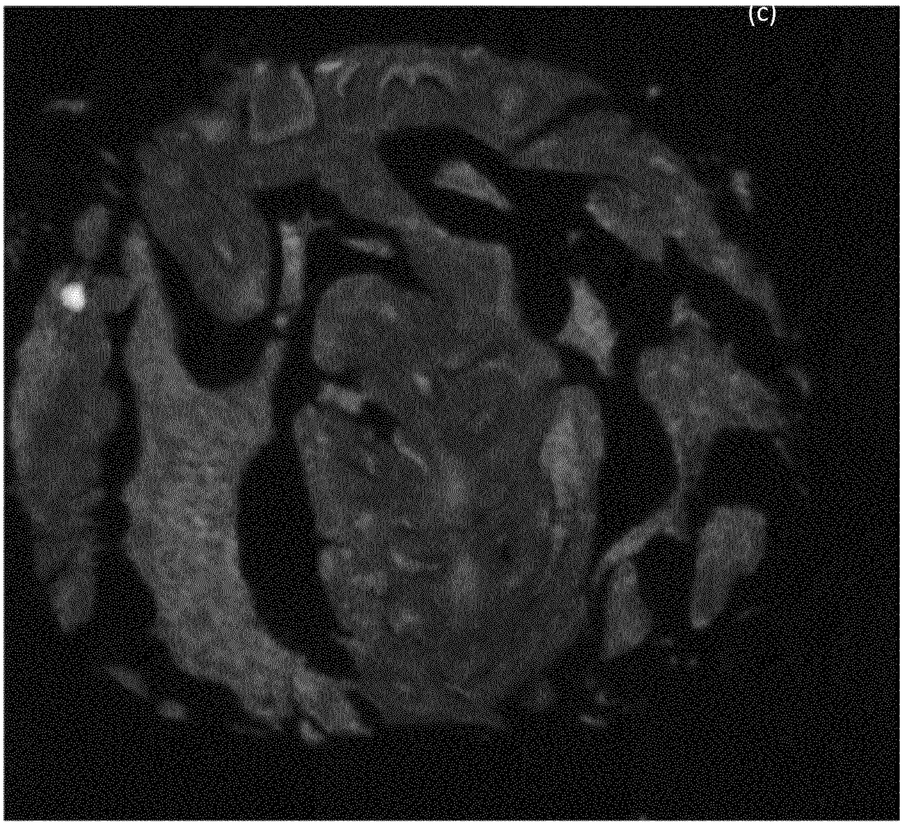


Fig. 6C

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/072021

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01J3/28 G01J3/45 G01J1/58
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	S. JUNAID ET AL: "Upconversion based spectral imaging in 6 to 8 [mu]m spectral regime", PROCEEDINGS OF SPIE, vol. 10088, 20 February 2017 (2017-02-20), page 100880I, XP055555756, 1000 20th St. Bellingham WA 98225-6705 USA ISSN: 0277-786X, DOI: 10.1117/12.2250538 ISBN: 978-1-5106-2099-5	1-11,13, 18,19
A	pages 1,3,4,7; figures 1b,2,3 -----	12,14-17

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
12 November 2019	02/12/2019

Name and mailing address of the ISA/	Authorized officer
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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	AJANTA BARH ET AL: "Ultra-broadband mid-wave-IR upconversion detection", OPTICS LETTERS, vol. 42, no. 8, 15 April 2017 (2017-04-15), page 1504, XP055557165, US ISSN: 0146-9592, DOI: 10.1364/OL.42.001504 page 1505, column 2 - page 1506, column 2; figures 1-4 -----	1-19
A	WO 2018/007572 A1 (UNIV DANMARKS TEKNISKE [DK]) 11 January 2018 (2018-01-11) page 17, line 19 - page 18, line 6; figures 9,11-11 -----	1-19

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/072021

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2018007572 A1	11-01-2018	EP 3482175 A1	15-05-2019
		US 2019242747 A1	08-08-2019
		WO 2018007572 A1	11-01-2018