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Near infrared spectro-interferometer using femtosecond laser written GLS embedded waveguides and nano-scatterers

G. MARTIN,^{1,*} M. BHUYAN,² J. TROLES,³ C. D'AMICO,² R. STOIAN,² AND E. LE COARER¹

¹Univ. Grenoble Alpes/CNRS, IPAG, F-38000 Grenoble, France

²Laboratoire Hubert Curien, UMR 5516 CNRS, Université de Lyon, Université Jean Monnet, 42000 St. Etienne, France

³Chemical Sciences Institute of Rennes, UMR 6226 CNRS, University of Rennes I, 35042 Rennes, France

*guillermo.martin@univ-grenoble-alpes.fr

Abstract: Guided optics spectrometers can be essentially classified into two main families: based on Fourier transform or dispersion. In the first case, an interferogram generated inside an optical waveguide and containing the spectral information is sampled using spatially distributed nanodetectors. These scatter quasi-non-perturbingly light into the detector that is in contact with the waveguide, helping to reconstruct the stationary wave. A dedicated FFT processing is needed in order to recover the spectrum with high resolution but limited spectral range. Another way is to directly disperse the different wavelengths to different pixels, either introducing differential optical path in the same propagation plane (multiple Mach-Zehnder interferometers or Arrayed Waveguides Gratings), or using a periodic structure to perpendicularly extract the optical signal confined in a waveguide (photonic crystals or surface gratings), and by means of a relay optics, generate the spectrum on the Fourier plane of the lens, where the detector is placed. Following this second approach, we present a laser-fabricated high-resolution compact dispersive spectro-interferometer ($R > 2500$, 30nm spectral range at $\lambda = 1560\text{nm}$), using four parallel waveguides that can provide up to three non-redundant interferometric combinations. The device is based on guided optics technology embedded in bulk optical glass. Ultrafast laser photoinscription with 3D laser index engineering in bulk chalcogenide Gallium Lanthanum Sulfide glass is utilized to fabricate large mode area waveguides in an evanescently-coupled hexagonal multicore array configuration, followed by subsequent realization of nanoscaled scattering centers via one dimensional nanovoids across the waveguide, written in a non-diffractive Bessel configuration. A simple relay optics, with limited optical aberrations, reimages the diffracted signal on the focal plane array, leading to a robust, easy to align instrument.

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References and links

1. E. Le Coarer, S. Blaize, P. Benech, I. Stefanon, A. Morand, G. Lerondel, G. Leblond, P. Kern, J.-M. Fedeli, and P. Royer, "Wavelength-scale stationary-wave integrated Fourier-transform spectrometry," *Nat. Photonics* **1**(8), 473–478 (2007).
2. M. Florjańczyk, P. Cheben, S. Janz, A. Scott, B. Solheim, and D.-X. Xu, "Multiaperture planar waveguide spectrometer formed by arrayed Mach-Zehnder interferometers," *Opt. Express* **15**(26), 18176–18189 (2007).
3. G. Douglass, F. Dreisow, S. Gross, S. Nolte, and M. J. Withford, "Towards femtosecond laser written arrayed waveguide gratings," *Opt. Express* **23**(16), 21392–21402 (2015).
4. S. Pathak, P. Dumon, D. Van Thourhout, and W. Bogaerts, "Comparison of AWGs and echelle gratings for wavelength di-vision multiplexing on silicon-on-insulator," *IEEE Photonics J.* **6**(5), 1–9 (2014).
5. A. Z. Subramanian, E. Ryckeboer, A. Dhakal, F. Peyskens, A. Malik, B. Kuyken, H. Zhao, S. Pathak, A. Ruocco, A. De Groote, P. Wuytens, D. Martens, F. Leo, W. Xie, U. D. Dave, M. Muneeb, P. Van Dorpe, J. Van

- Campenhout, W. Bogaerts, P. Bienstman, N. Le Thomas, D. Van Thourhout, Z. Hens, G. Roelkens, and R. Baets, "Silicon and silicon nitride photonic circuits for spectroscopic sensing on-a-chip," *Photonics Res.* **3**(5), B47–B59 (2015).
6. G. Roelkens, U. Dave, A. Gassenq, N. Hattasan, C. Hu, B. Kuyken, F. Leo, A. Malik, M. Muneeb, E. Ryckeboer, S. Uvin, Z. Hens, R. Baets, Y. Shimura, F. Gencarelli, B. Vincent, R. Loo, J. Van Campenhout, L. Cerutti, J. B. Rodriguez, E. Tournié, X. Chen, M. Nedeljkovic, L. Mashanovich, L. Shen, N. Healy, A. C. Peacock, X. Liu, R. Osgood, and W. Green, "Silicon-based heterogeneous photonic integrated circuits for the mid-infrared," *Opt. Mater. Express* **3**(9), 1523–1536 (2013).
 7. N. K. Pervez, W. Cheng, Z. Jia, M. P. Cox, H. M. Edrees, and I. Kyriassis, "Photonic crystal spectrometer," *Opt. Express* **18**(8), 8277–8285 (2010).
 8. T. Katchalski, G. Levy-Yurista, A. Friesem, G. Martin, R. Hierle, and J. Zyss, "Light modulation with electro-optic polymer-based resonant grating waveguide structures," *Opt. Express* **13**(12), 4645–4650 (2005).
 9. I. Avrutsky, K. Chaganti, I. Salakhutdinov and G. Auner, "Concept of a miniature optical spectrometer using integrated optical and micro-optical components," *Appl. Opt.* **45**(30), 7811–7817 (2006).
 10. K. Chaganti, I. Salakhutdinov, I. Avrutsky, and G. W. Auner, "A simple miniature optical spectrometer with a planar waveguide grating coupler in combination with a plano-convex lens," *Opt. Express* **14**(9), 4064–4072 (2006).
 11. M. Deubel, G. von Freymann, M. Wegener, S. Pereira, K. Busch and C. M. Soukoulis, "Direct laser writing of three-dimensional photonic-crystal templates for telecommunications," *Nat. Mater.* **3**(7), 444–447 (2004).
 12. N. Ancombe, "Direct laser writing," *Nat. Photonics* **4**(1), 22–23 (2010).
 13. M. M. Vogel, M. Abdou-Ahmed, A. Voss, and T. Graf, "Very-large-mode-area, single-mode multicore fiber," *Opt. Lett.* **34**(18), 2876–2878 (2009).
 14. G. Cheng, C. D'Amico, X. Liu, and R. Stoian, "Large mode area waveguides with polarization functions by volume ultrafast laser photoinscription of fused silica," *Opt. Lett.* **38**(11), 1924–1926 (2013).
 15. C. D'Amico, G. Cheng, C. Maclair, J. Troles, L. Calvez, V. Nazabal, C. Caillaud, G. Martin, B. Arezki, E. LeCoarer, P. Kern, and R. Stoian, "Large-mode-area infrared guiding in ultrafast laser written waveguides in Sulfur-based chalcogenide glasses," *Opt. Express* **22**(11), 13091–13101 (2014).
 16. R. Stoian, C. D'Amico, M. Bhuyan, and G. Cheng, "Ultrafast laser photoinscription of large-mode-area waveguiding structures in bulk dielectrics," *J. Opt. Las. Technol.* **80**, 93 (2016).
 17. M. K. Bhuyan, F. Courvoisier, P. A. Lacourt, M. Jacquot, R. Salut, L. Furfaro, and J. M. Dudley, "High aspect ratio nanochannel machining using single shot femtosecond Bessel beams," *Appl. Phys. Lett.* **97**(8), 081102 (2010).
 18. M. Bhuyan, P. K. Velpula, J. P. Colombier, T. Olivier, N. Faure, and R. Stoian, "Single shot high aspect ratio bulk nanostructuring of fused silica using chirp controlled ultrafast laser Bessel beams," *Appl. Phys. Lett.* **104**(2), 021107 (2014).
 19. P. K. Velpula, M. Bhuyan, F. Courvoisier, H. Zhang, J. P. Colombier, and R. Stoian, "Spatio-temporal dynamics in nondiffractive Bessel ultrafast laser nanoscale volume structuring," *Laser Photonics Rev.* **2**(2), 230–244 (2016).
 20. J. Woillez, R. Akeson, M. Colavita, J. Eisner, A. Ghez, J. Graham, L. Hillenbrand, R. Millan-Gabet, J. Monnier, J.-U. Pott, S. Ragland, P. Wizinowich, E. Appleby, B. Berkey, A. Cooper, C. Felizardo, J. Herstein, M. Hrynevych, O. Martin, D. Medeiros, D. Morrison, T. Panteleeva, B. Smith, K. Summers, K. Tsubota, C. Tyau, and E. Wetherell, "ASTRA: ASTrometry and phase-Referencing Astronomy on the Keck interferometer," *Proc. SPIE* **7734**, 773412 (2010).
 21. K.-H. Hofmann, M. Heininger, W. Jaffe, S. Kraus, B. Lopez, F. Millour, D. Schertl, G. Weigelt, and S. Wolf, "Aperture-synthesis imaging with the mid-infrared instrument MATISSE," *Proc. SPIE* **7013**, 70133Y (2008).
 22. E. Huby, G. Perrin, F. Marchis, S. Lacour, T. Kotani, G. Duchêne, E. Choquet, E. L. Gates, J. M. Woillez, O. Lai, P. Fédou, C. Collin, F. Chapron, V. Arslanyan, and K. J. Burns, "FIRST, a fibered aperture masking instrument-I. First on-sky test results," *Astron. Astrophys.* **541**, A55 (2012).
 23. S. Lacour, V. Lapeyrère, L. Gauchet, S. Arroud, R. Gourgues, G. Martin, S. Heidmann, X. Haubois and G. Perrin, "CubeSats as pathfinders for planetary detection: the FIRST-S satellite," *Proc. SPIE* **9143**, 91432N (2014).
 24. A. Ródenas, G. Martin, B. Arezki, N. Psaila, G. Jose, A. Jha, L. Labadie, P. Kern, A. Kar, and R. Thomson, "Three-dimensional mid-infrared photonic circuits in chalcogenide glass," *Opt. Lett.* **37**(3), 392–394 (2012).
 25. S. Juodkazis, K. Nishimura, S. Tanaka, H. Misawa, E. G. Gamaly, B. Luther-Davies, L. Hallo, P. Nicolai, and V. Tikhonchuk, "Laser-induced microexplosion confined in the bulk of a sapphire crystal: evidence of multimegabar pressures," *Phys. Rev. Lett.* **96**(16), 166101 (2006).
 26. N. Cvetojevic, N. Jovanovic, J. Lawrence, M. Withford, and J. Bland-Hawthorn, "Developing arrayed waveguide grating spectrographs for multi-object astronomical spectroscopy," *Opt. Express* **20**(3), 2062–2072 (2012).
 27. L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, and R. Osellame, "Polarization Entangled State Measurement on a Chip," *Phys. Rev. Lett.* **105**(20), 200503 (2010).
 28. K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, "Writing waveguides in glass with a femtosecond laser," *Opt. Lett.* **21**(21), 1729–1731 (1996).
 29. M. Hughes, W. Yang, and D. Hewak, "Fabrication and characterization of femtosecond laser written waveguides in chalcogenide glass," *Appl. Phys. Lett.* **90**(13), 131113 (2007).

30. S. Minardi, G. Cheng, C. D'Amico, and R. Stoian, "A low-power-threshold photonic saturable absorber in nonlinear chalcogenide glass," *Opt. Lett.* **40**(2), 257–259 (2015).
31. F. Thomas, S. Heidmann, M. de Mengin, N. Courjal, G. Ulliac, A. Morand, P. Benech, E. Le Coarer, and G. Martin, "First Results in Near and Mid IR Lithium Niobate-Based Integrated Optics Interferometer Based on SWIFTS-Lippmann Concept," *J. Lightwave Technol.* **32**(22), 4338–4344 (2014).
32. G. Martin, F. Thomas, S. Heidmann, M. de Mengin, N. Courjal, G. Ulliac, A. Morand, P. Benech, P. Kern, and E. Le Coarer, "High Resolution TE&TM Near Infrared Compact Spectrometer based on Waveguide Grating Structures," *Proc. SPIE* **9516**, 95160C (2015).

1. Introduction

The aim of this work is to propose a development and fabrication concept for an integrated high resolution compact spectro-interferometer for spatial and drone applications, using ultrafast laser photoinscription and embedded fabrication in bulk optical glass. Our approach to achieve spectral resolution is to use a waveguide grating to sample the optical signal within a laser-fabricated optical guide and relay optics to generate the spectrum in the Fourier plane with limited optical aberrations. The spectrum is thus obtained without any moving part, limiting vibration effects and enhancing robustness of the spectrometer. In addition, the multichannel realization has allowed to show non-redundant interferometry using the same optical device. From the material processing point of view, a multiscale 3D ultrafast laser processing technique using beam engineering is demonstrated, enabling standard waveguide fabrication and nanoscale scatterers to sample optical signals.

Integrated optics spectrometers have been proposed in a variety of ways: generation of an interferogram inside an optical waveguide, and use of nanodetectors in order to sample the signal, followed by a dedicated FFT processing in order to recover the spectrum with high resolution but limited spectral range [1]. Another way is to directly disperse the different wavelengths to different pixels, either introducing differential optical path in the same propagation plane (multiple Mach-Zehnder interferometers [2], Arrayed Waveguides Gratings [3] or Planar Concave Gratings [4]). These last approaches are highly mature, using silicon photonics technology which means robust developments and high performances [5,6] but also complex fabrication procedures and difficulties to couple external light to the highly confined, small section mode of the silicon waveguide. Other approaches are using a periodic structure to perpendicularly extract the optical signal confined in a waveguide (photonic crystals [7] or surface gratings [8]), and by means of a relay optics, generate the spectrum on the Fourier plane of the lens [9, 10], where the detector is placed. This last approach is limited in efficiency as most of the signal is expected to be radiated towards the substrate. However, directivity of the flux is optimal in this configuration, allowing for easier relay optics. A second drawback of this approach is that using a unique lens to focus light diffracted by the grating, chromatic aberrations appear (the focal point changes with wavelength), so that in order to reach ideal sampling one would need to move the detector along the Locus line. Finally, most of the preceding techniques are based on classical lithographic techniques. In this work, we present an alternative approach to fabricate the diffraction grating (the rapidly growing technique of direct laser writing of photonic structures [11, 12]) used to fabricate the large mode area waveguide (multicore approach [13–16]) and the nanoscale diffraction grating (Bessel voids [17–19]). The extracted signal is then coupled to an optical set-up where aberrations are limited by the use of an afocal optical system to image a series of several sampled parallel waveguides. But the most important feature of the device presented hereunder is the possibility to obtain the spectrum of different sources simultaneously, as each waveguide represents one input source and is re-imaged on the detector (focused mode). Or alternatively, in the defocused mode, it allows to overlap the different inputs (here, up to four telescopes) using a non-redundant configuration, that can be used in spectro-interferometry applications. This can be used in a variety of telescopes arrays (VLTI, CHARA, KECK) in order to reduce the footprint of spectro-interferometry projects such as ASTRA/KECK [20] or aperture synthesis projects such as MATISSE/VLTI [21], or aperture masking concepts (FIRST [22]) where spectrum together with the pairwise combination of signal coming from

the telescopes or sub-apertures is used to generate interference fringes, where amplitude and phase of the fringes are the observables. Finally, size reduction of spectro-interferometers is compulsory to develop spatial projects such as FIRST-LITHIUM, a proof of concept cubesat interferometer that will test two telescope beam combination [23].

The second issue is the demonstration of a multiscale 3D laser processing technique enabling both micron-sized refractive index engineering [24] and nanoscaled structures [25] together with large mode area waveguides, in order to improve coupling and flux collection of the incident optical beam. A non-linear laser processing renders the optical design flexible and mechanically stable, embedded in bulk optical glasses [26, 27].

The manuscript is organized as follows. The fabrication technique is described, followed by the optical characterization of its optical functions. The conclusion section resumes the optical performances we have obtained in our near infrared spectro-interferometer prototype.

2. Sample fabrication and simulations

The first part in the construction relies on the fabrication of embedded waveguides and the realization of a regular pattern of scattering centers. In order to pave the way to mid-infrared applications, we decided to use commercial GLS glass (transparent up to 12 microns) and use a pulsed femtosecond laser to engrave the optical waveguides [28–30], as well as the sampling centers. The waveguides were fabricated using an ultrafast laser photoinscription technique set in a longitudinal scan configuration, with a scan of the laser spot along the propagation axis. High repetition rate (100 kHz) 150 fs laser radiation at 800 nm central wavelength from a Ti:sapphire amplified laser system was used in a moderate focusing configuration ($NA = 0.3$) along with an energy compensating scheme balancing optical aberrations at increasing processing depth. Thus an input power varying from 230 mW down to 50 mW was used for a 300 μm scan speed. The irradiation source is equally equipped with a pulse envelope control unit in the time and space domains based on spectral and spatial phase modulation. Positively chirped 1.2 ps laser pulses were used to keep nonlinear distortions at a low level. The procedure is described in [15]. The GLS material is particularly interesting for laser photoinscription technique as it shows a large processing window of positive Type I index changes. A multicore configuration is used to achieve large mode area guiding in the NIR and MIR with single mode characteristics. This is based on a centered hexagonal arrangement of 37 parallel waveguides (and 5 μm radial separation between individual traces) with an index contrast in the range of 10^{-4} - 10^{-3} . A view on the multicore waveguide structure and mode diameter at 1550nm is given in Fig. 1. Injection in the central trace and evanescent coupling towards neighboring waveguides ensures coherent modal superposition [13, 14] and the formation and propagation of a single mode in the GLS transparency window [15]. This allows to realize a large area mode, 20 μm FWHM, extending over the physical section of the waveguide.

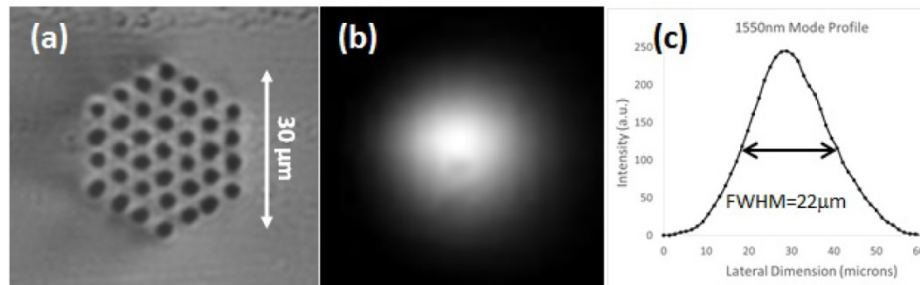


Fig. 1. (a) Multicore hexagonal single mode waveguide fabricated in GLS using short laser pulses. (b) Image of the mode obtained using a 1550nm SLED (same scale as (a)) and (c) mode profile showing large FWHM.

We fabricated a set of four large-mode-area channel waveguides [13–15, 30] aligned in a plane, with a center-to-center separation of $250\ \mu\text{m}$ and buried at $800\ \mu\text{m}$ from the surface. In a second step, a non-diffractive irradiation procedure [17, 18] was used to generate a series of one-dimensional voids, transverse to the waveguides, with a characteristic section below $500\ \text{nm}$ and an axial dimension above of $150\ \mu\text{m}$, separated by $30\ \mu\text{m}$ (See Fig. 2). An ultrafast Ti-Sapphire amplified system at $1\ \text{kHz}$ repetition rate is used. Picoseconds pulse Bessel beams of 10° half-cone angle (inside the material) were employed to generate enough energy concentration in order to create localized unidimensional micro-explosion, where the lateral release of pressure creates one-dimensional axially-uniform cavities, to avoid nonlinear distortions and to ensure extended uniform voids [18, 19].

The main interest of laser writing for making the elongated nanovoids is that we can easily cover a sampling length of $1\ \text{cm}$, without mask replacement, in a very short time (few seconds). Besides, we can adjust the position of the hole with respect to the waveguide, in order to optimize the extraction efficiency. The nanovoids are aligned in close contact to the last waveguide of the hexagonal array. The scattering efficiency depends on the cross-sections of the voids. For cross-sections between $100\ \text{nm}$ and $500\ \text{nm}$ and positions in the vicinity of the $1/e^2$ of the mode, scattering efficiencies ranging from 10^{-2} to 10^{-3} were estimated by FDTD calculations. An overview of the optical device with side and top views is given in Fig. 2.

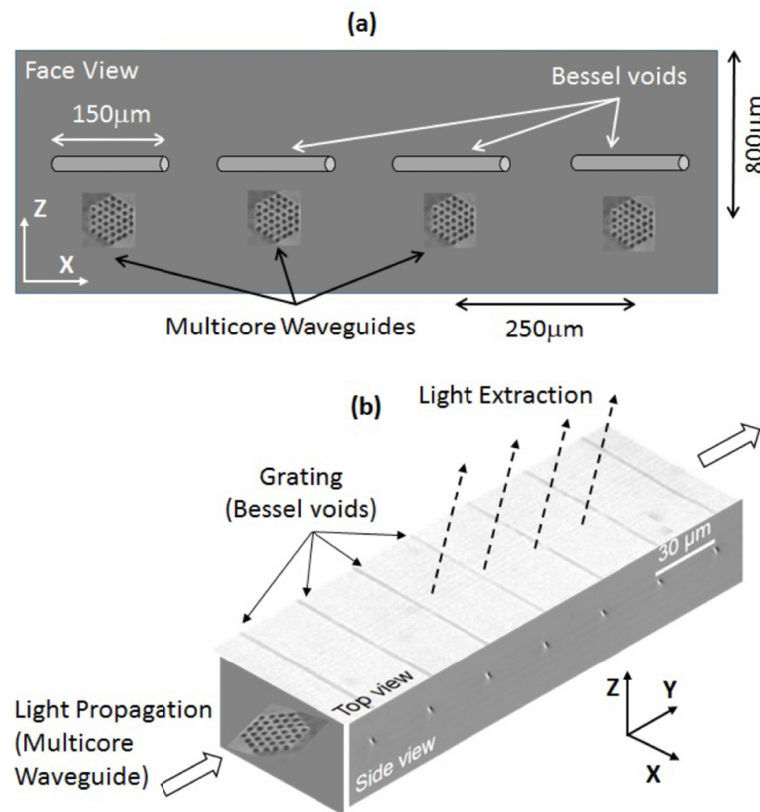


Fig. 2. (a) Face view of the whole structure showing four parallel multicore waveguides and their respective Bessel sampling centers above them. Typical dimensions are given in the figure. (b) 3D view of the device showing the disposition of the nanovoids array positioned transverse to the waveguide and the axis orientation.

In similar works [9] in a planar configuration, a large waveguide (4mm wide) is used, so that the collimated beam sampled by a large scattering center is focused in a single spot. However, such a large waveguide implies multimode behavior, resulting in overlapping between different modes with different wavelengths. On the contrary, using a single mode, narrow waveguide, one avoids high order diffraction modes, but the radiation pattern becomes angularly large. Besides, as has been shown in full vectorial calculations, surface gratings are not the most efficient approach, as most of the flux is radiated towards the substrate [31]. Here, as the sampling centers are fabricated inside the material, a symmetric radiation pattern is expected, resulting in a more efficient flux extraction towards the surface. In order to efficiently recover the flux, and discriminate eventually different order modes, we have developed a simple set-up using a cylindrical lens for collecting the wide angle flux and focus different wavelengths at different pixels, and a second optical stage to reduce aberrations, disperse laterally diffraction modes and avoid overlapping.

3. Optical set-up

The optical set-up we propose is drawn in Fig. 3:

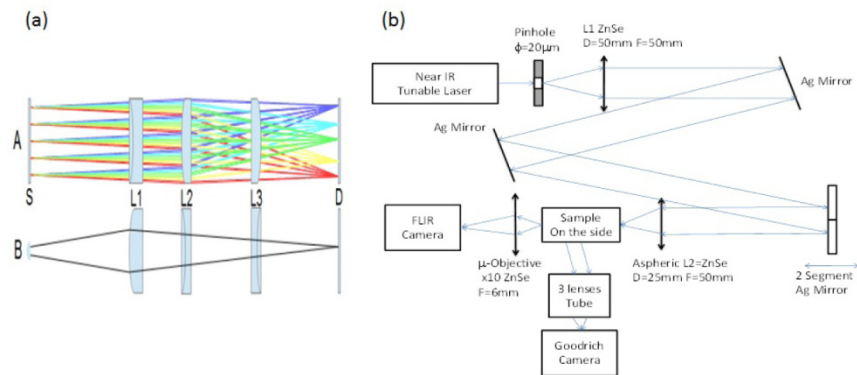


Fig. 3. Optical set-up. (a) Detail of the 3 Lenses Tube system. A and B represent the channel waveguide in side and front view respectively, and D is the detector plane. (b) Detail optical set-up showing the source, waveguide injection, and vertical collection of the radiated flux as well as direct transmission to the camera.

The source is a near IR tunable laser, from Yenista, that can be tuned from 1500 to 1620 nm. A single mode output fiber is placed at the focus of a ZnSe ($f = 50$ mm) aspherical lens that collimates the beam and is directed towards a two segment mirror. This consists of two square 1" Ag mirrors that are set on two independent tip-tilt and translation axis. The two beams are then directed towards a second ZnSe ($f = 50$ mm) aspherical lens, with a small relative angle, that allows to inject light into two adjacent waveguides. In order to check proper injection into the waveguides, an image of the waveguide output is obtained on the FLIR camera (Fig. 4(a)) and from above using a simple microscope objective instead of the lens triplet (Fig. 4(b)).

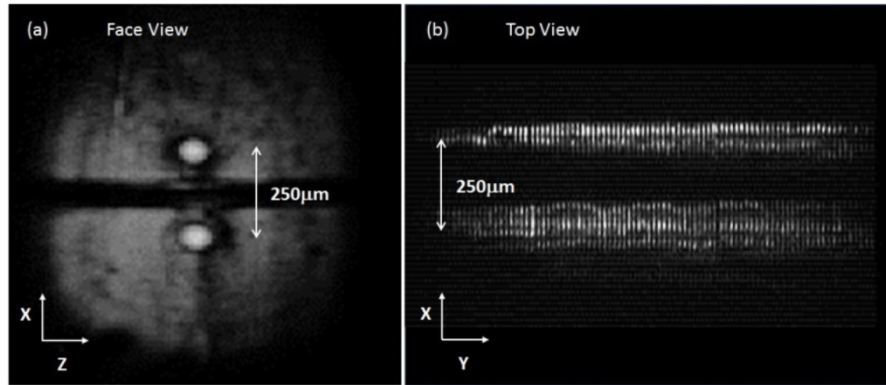


Fig. 4. Near IR observation of two parallel waveguides and the sampling centers when illuminated with a 1.56μm laser. (a) Direct transmission on the FLIR camera, showing the two modes of two adjacent channel waveguides. (b) Top view as signal is extracted with the sampling centers and imaged on the Goodrich Camera using a simple microscope objective.

Vertical characterization of the extracted signal (Fig. 4(b)) is achieved using a three cylindrical lenses tube (Fig. 3(a)), allowing to image the diffracted signal from the nanovoids to be detected on a Goodrich near IR camera. The L1 cylindrical lens ($f_1 = 150\text{mm}$), is aligned perpendicular to the channel waveguide and focuses the angularly wide diffracted light from the grating into a line on the CCD (Fig. 3(a), inset B). L2 hemi-cylindrical ($f_2 = 100\text{mm}$) is perpendicular to the L1 axis. The hemi-cylindrical L3 ($f_3 = 100\text{mm}$), which axis is also perpendicular to L1 is used with L2, to reduce aberrations, by creating an afocal configuration. In the present study, L2 and L3 are exactly centered midway between the waveguide and the detector, making a 1:1 image of the waveguide onto the CCD. With this optical set-up, L2 and L3 focus different wavelengths at different areas on the CCD (Fig. 3(a) inset A), along the direction of the channel waveguide. The total volume of the spectro-interferometer is thus 320 cm^3 (height 200mm, width and length 40mm), including the sample, the relay optics and the detector. Note that once the flux is injected in the spectrometer (i.e. using a fibered V-groove) there is no moving part up to the detector, interference fringes and spectral dispersion are obtained directly on the detector. In order to reduce the footprint, a tradeoff can be obtained by reducing the focal length, and therefore the spectral resolution of the device (see section 4 below).

4. Theoretical background

The main equations we have to use here are the theoretical spectral resolution and the link between length of the sampling region and size of the diffraction spot on the detector. The theoretical background has been developed elsewhere [32], we will use here the main results adapted to the present device configuration. The spectral range $d\lambda$ that is comprised within the dimensions of a pixel, dx , is given by:

$$d\lambda = \frac{\lambda \cdot dx}{f \cdot n} \quad (1)$$

which allows us to determine the spectral resolution: $R = \lambda/\partial\lambda = f \cdot n/\partial x$, as far as we know the focal length of L1 ($f = f_1$), the refractive index of the waveguide, n , and the central wavelength, λ .

Using $f_1 = 150\text{mm}$, $n = 2.3$, $\partial x = 25\mu\text{m}$ (Goodrich pixel size) and assuming that the sampled length over the waveguide is long enough so that resolution is limited to the pixel size, we should be able to obtain $R = 13800$. Note that resolution is only related to focal length, refractive index and pixel size (assuming that the required sampling region D is

achieved). Thus, resolution is not dependent on the wavelength, nor on the number and density of sampling grooves.

The main constraint is that the length of the sampling region D must be:

$$D \geq \frac{1,22 \cdot \lambda \cdot f}{2dx} \quad (2)$$

In our case, with $\lambda = 1.56 \mu\text{m}$, and $f_l = 150 \text{ mm}$, $D = 10 \text{ mm}$, the diffraction limit of the optical system should be $\partial x = 13.7 \mu\text{m}$, which is well below the size of the pixel in the Goodrich detector, $25 \mu\text{m}$. It can be also understood that the spectral range that each pixel sees is expected to be $\partial \lambda = 0.11 \text{ nm}$.

5. Results

5.1 Spectral resolution

Following the optical set-up described before, we studied a waveguide grating consisting ca. 330 holes with a period of $30 \mu\text{m}$, realized by femtosecond laser writing. In order to determine the resolution of the set-up, a scan between 1560 and 1587 nm, was done:

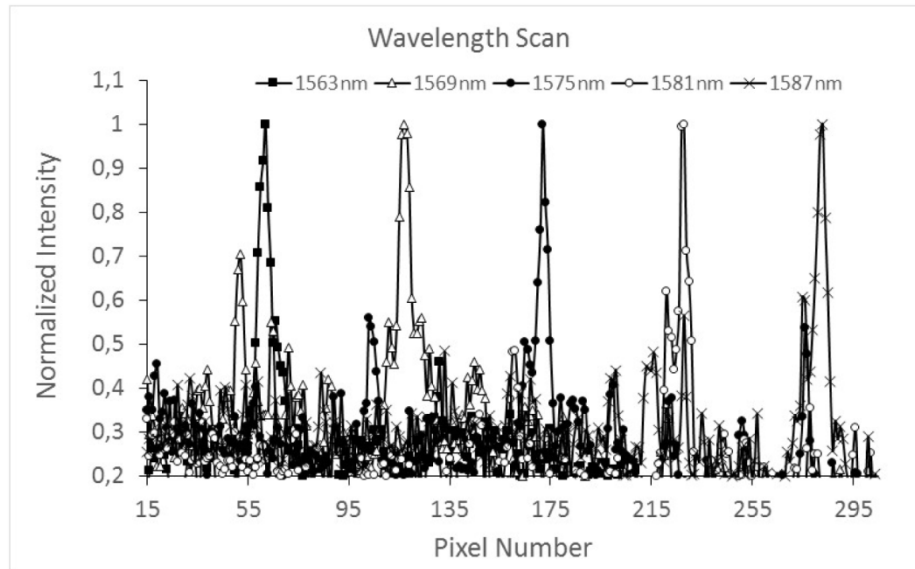


Fig. 5. Detected peak on an array of pixels, as the wavelength is scanned within the source tuning range. Side lobes are visible, due to inhomogeneous grating period fabrication, and induce crosstalk (see for example the secondary lobe at 1569nm (open triangles) close to the main peak at 1563nm (filled squares)).

As shown in the precedent figure, peak intensity moves on the detector as we scan the wavelength. The images on Fig. 5 show the short wavelength peak moving to the right as wavelength is increased. We can verify that a modification of 3 nm implies a peak shift of 30 pixels, that is, each pixel corresponds to 0.1 nm , which is the theoretical expected value. Due to the limited spectral window, as we scan from 1500 to 1620 nm , the peak will go from left to right until another diffraction order appears on the left. The total wavelength span on the detector is thus ca. 30 nm , whereas the experimental resolution, defined as the pixel distance between a maximum and the closest minimum is ca. 5 pixels, meaning 0.5 nm instead of the theoretical one of 0.1 nm . This discrepancy can be due to optical aberrations and/or lack of accuracy of the grating period. Moreover, we observe that side lobes appear and induce some crosstalk, due to the non uniformity of the grating. Indeed, we observe that for example the peak at 1569 nm (open triangles) presents a side lobe close to the 1563 nm peak (filled

squares). This effect is observed repeatedly as the wavelength is scanned, and clearly indicates that the grating is not periodically homogeneous. We achieved a measurement of the peak width as a function of the length of the sampling area, by masking progressively the surface of the sample, and thus reducing the number of Bessel voids involved in the signal extraction. As seen in Fig. 6 below, instead of following the theoretical $1/D$ law, the peak width decreases dramatically after the first microns of sampling centers but reaches a stable value around 4 pixels instead of the expected 1 pixel resolution, meaning that D is not the limiting factor.

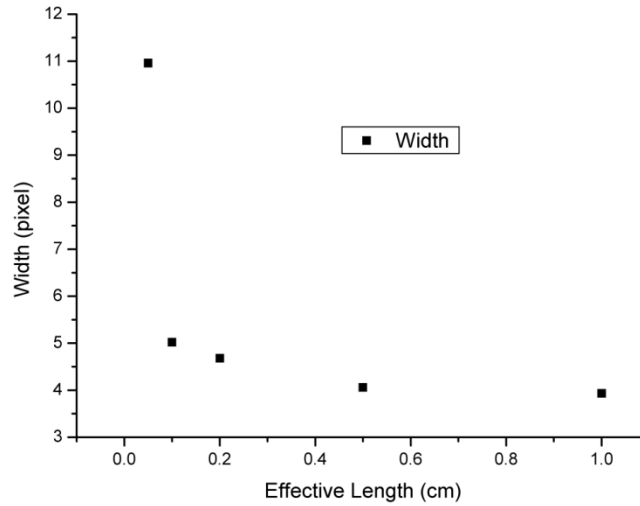


Fig. 6. Plot of the FWHM of the diffracted peak as a function of effective sampling length, showing a limiting value at 4 pixels, instead of 1 pixel theoretically expected. This result is obtained by progressively masking the sampling centers.

The results obtained for width evolution and the observation of secondary lobes aside the main diffracted peak suggest that the limiting factor is the accuracy of the sampling centers period. Indeed, we can calculate the constraint on the periodicity, by starting from the fundamental law of diffraction gratings. Considering orthogonal incidence between the waveguide beam and the grating, the diffraction angle θ can be deduced from:

$$N_{\text{eff}} + \sin \theta = m \cdot \frac{\lambda}{\Lambda} \quad (3)$$

where N_{eff} is the effective index of the guided mode, Λ is the period of the grating and m is the diffraction order. Deriving with respect to the period, we obtain:

$$\cos \theta \cdot \partial \theta = m \cdot \frac{\lambda}{\Lambda^2} \partial \Lambda \quad (4)$$

As $f \cdot \partial \theta = \partial x$:

$$\partial x = m \cdot \frac{f}{\cos \theta} \cdot \frac{\lambda}{\Lambda^2} \partial \Lambda \quad (5)$$

Assuming vertical observation ($\theta = 0$) and identifying $\partial x = \text{pixel size}$:

$$\partial \Lambda \approx \frac{\Lambda^2}{f \lambda} \partial x \quad (6)$$

So for $f = 10 \text{ cm}$, $\lambda = 1 \text{ } \mu\text{m}$, $\Lambda = 10 \text{ } \mu\text{m}$ and pixel size $= \partial x = 10 \text{ } \mu\text{m}$, we obtain a constraint on the accuracy of the grating as high as $\partial \Lambda = 10 \text{ nm}$ in order not to leak to

adjacent pixels. Any error stronger than this value will imply flux leakage to adjacent pixels. Reaching this quality is expected to be difficult for sequential laser writing techniques. This implies that our laser written waveguides are not accurate enough to ensure a diffraction limited working of the system. Despite this limitation, this forecasts nevertheless the potential of laser photoinscription techniques for fabricating surface gratings. Mechanical deficiencies can be overcome by advanced laser synchronization methods and stage performances.

5.2 Simultaneous two Inputs Injection: spectro-interferometer

If we inject simultaneously two contiguous channel waveguides, we can then obtain the spectrum in the horizontal direction for each input channel. With our set-up, two channel waveguides with 250 μm separation are imaged on the detector with 6 pix separation. We then defocus the system, by varying the distance between the triplet and the sample surface, in order to obtain overlapping of the two diffracted peaks (see Fig. 7). Typical Young interference fringes between the two sources appear in the vertical direction.

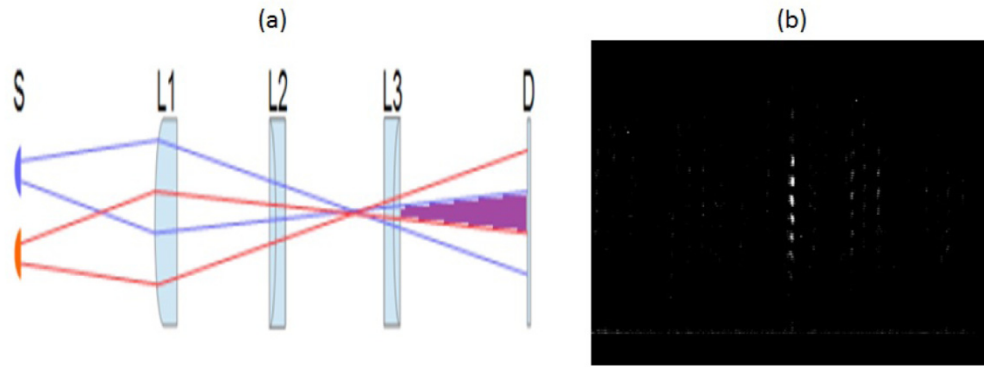


Fig. 7. (a) Optical set-up showing overlapping of the signal extracted from two adjacent waveguides as the triplet is defocused from the source plane. (b) Young fringes obtained on the detector for a monochromatic source when two adjacent channel waveguides are simultaneously injected.

We obtain fringes vertically, in a band that is going to move horizontally as we scan the wavelength of the source (see Fig. 8). If we restrict each vertical band of 8 pixels to one wavelength, we can use the 320 horizontal pixels of the camera, to make 40 spectral channels, and vertically, we can use the Young fringes to obtain the non redundant fringes for multiple inputs (i.e. multi-telescope inputs).

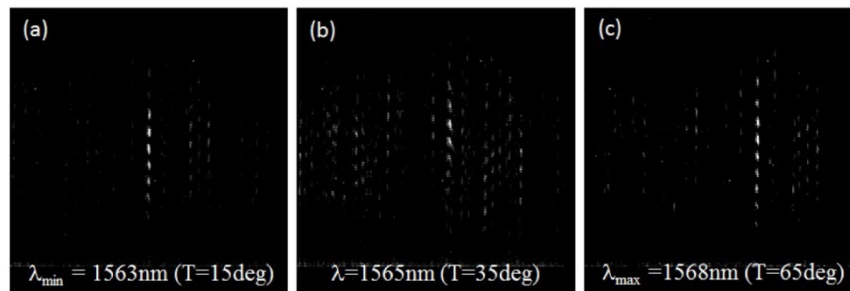


Fig. 8. Image of the vertical interference fringes as they move on the detector as the wavelength is tuned (a) $\lambda = 1563\text{nm}$, (b) $\lambda = 1565\text{nm}$ and (c) $\lambda = 1568\text{nm}$.

Note that in principle, it could be possible to distinguish between the periods of the Young fringes at different wavelengths, however this is experimentally difficult to obtain. Indeed, if we consider the expression of the period, $i = \lambda D/d$, and calculate its value as a function of the

defocusing distance ($D = 5$ cm), waveguide separation ($d = 250$ μm), we obtain (using the extreme values of the Yenista source, 1500-1620 nm and knowing that the pitch size on the Goodrich camera is 25 $\mu\text{m}/\text{pixel}$): $i_{\min}(\lambda_{\min}) = 12$ pix and $i_{\max}(\lambda_{\max}) = 12.96$ pix. Knowing that we can't visualize the whole tuning range but are limited to ca. 30 nm in the camera window, this means that the period of the Young fringes is essentially the same as seen from the detector. However, the Young fringes are efficiently discriminated when different pairs of waveguides are injected. We have compared the FFT signal of the vertical fringes for two close waveguides (separation 250 μm) with two far waveguides (500 μm) (see Fig. 9):

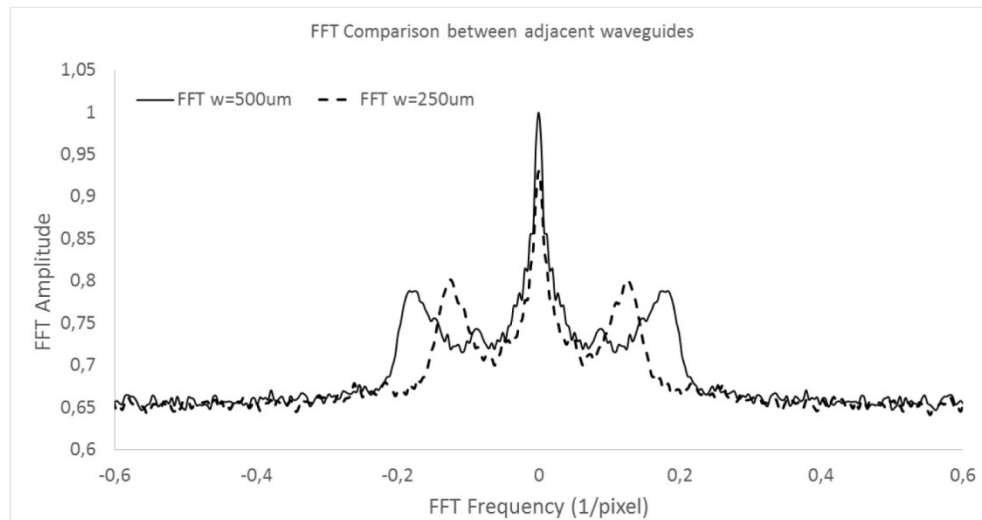


Fig. 9. FFT of the vertical fringes obtained at 1568 nm when two parallel waveguides, but with different lateral separation, are injected simultaneously. Continuous line, 500 μm separation; Dashed line, 250 μm separation.

We can observe the difference between two different set of fringes, depending on channel waveguide separation. The information on the fringe visibility of different pairs of waveguides appears at different Fourier frequencies, although in this preliminary measurement we observe some crosstalk (signal of the high frequency peak is still present at 0.12 pix^{-1} , where the low separation waveguides peak is centered). This confirms that we can use the vertical dimension of the detector for studying interference between sources (for example, two different collecting telescopes) whilst using the horizontal dimension for spectral dispersion, and thus obtain a spectro-interferometer in a single device.

6. Conclusion and perspectives

In this work we have presented a novel way to extract light from waveguides, using one-dimensional nanovoids engraved inside the bulk material, and re-image the different wavelengths on the detector using a lens triplet. A nonlinear bulk ultrafast laser fabrication method was used to achieve multiscale processing; from micron-sized waveguiding traces to nanoscaled scatterers. We have obtained the first results in the near IR spectral range, at telecom wavelengths using a compact spectro-interferometer design, embedded in the bulk, based on the diffraction of the signal confined in a single mode channel waveguide using a grating structure. The total volume is 320 cm^3 , including the sample, the relay optics and the detector and the experimental resolution is $R = 2760$, using $D = 10$ mm sampling length along the waveguide. Theoretically this value should be almost five times stronger, but is experimentally limited as the accuracy on the period of the sampling centers is very restrictive. We were able to image a laser tunable source, between 1563 and 1580 nm, allowing peak detection with ca. 0.4 nm resolution. Thus, with these grating and optics

dimensions, we can image wideband sources up to around $\Delta\lambda = 30$ nm. By designing the pixel size, focal length and refractive index of the waveguide, as well as the length of the diffraction grating, spectral resolution and spectral bandwidth could be easily tuned and eventually the total volume of the spectro-interferometer be reduced (by reducing the resolution). Our next step will be to improve the quality of the diffraction grating, in order to obtain accurate grating periods before looking to increase sampling length to improve resolution. Note that the 10 mm long grating only took a few seconds to fabricate as compared to long process for grating fabrication such as Focused Ion Beam. Results on the simultaneous injection of two parallel channel, either 250 μm or 500 μm separation, allowed us to obtain and clearly discriminate fringe amplitude in the Fourier space and opens the way to astrophotonic applications, such as multi-telescope interferometry and phase closure studies. Indeed, we plan to inject simultaneously three non-redundant waveguides, using a wide band source, in order to validate the spectro-interferometer for three inputs simultaneously and achieve the phase closure. These preliminary results are encouraging for light weight applications, such as drone and cubesat interferometry projects, where we expect this type of compact spectro-interferometers to be a good tradeoff between performances and fabrication time and cost.

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