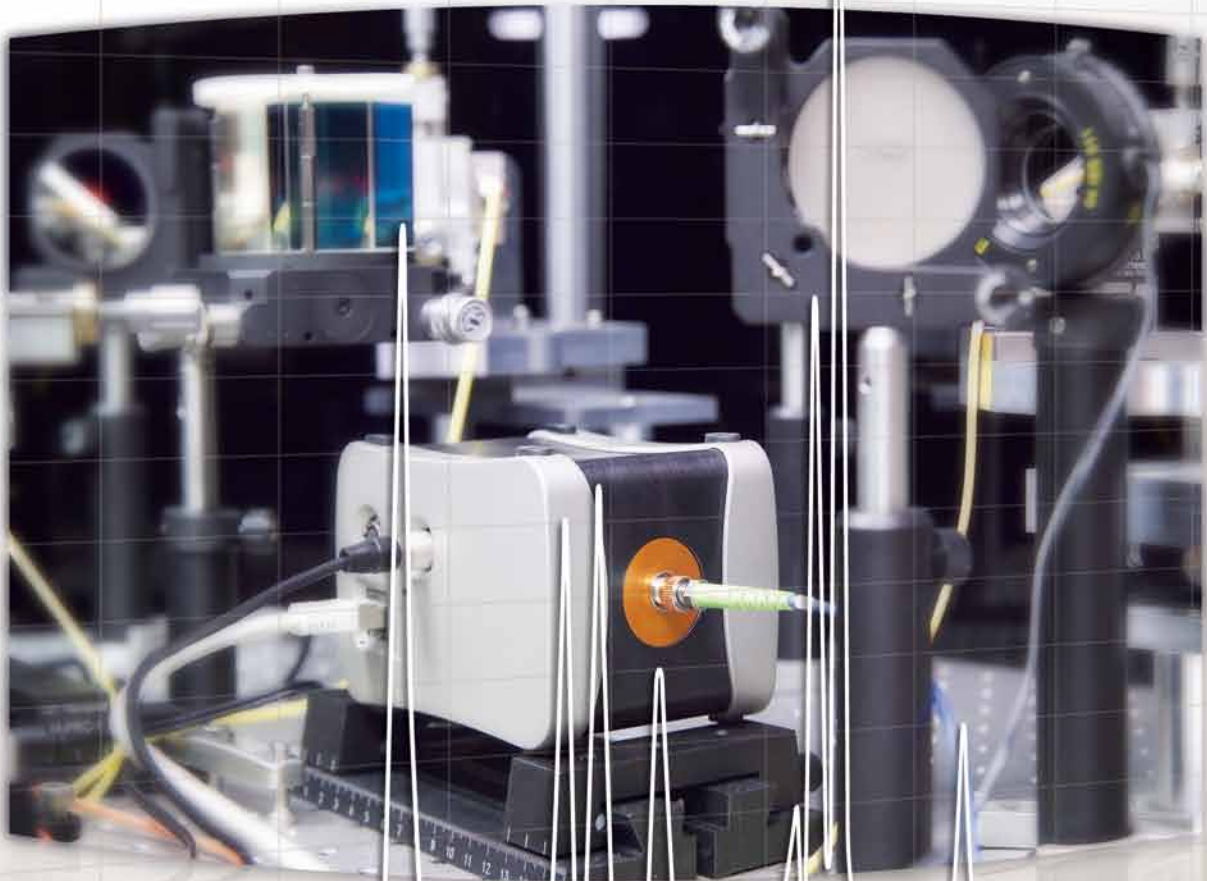


resolution
spectra systems

White paper

ZOOM Spectra

A Breakthrough in High-Performance Optical Spectroscopy



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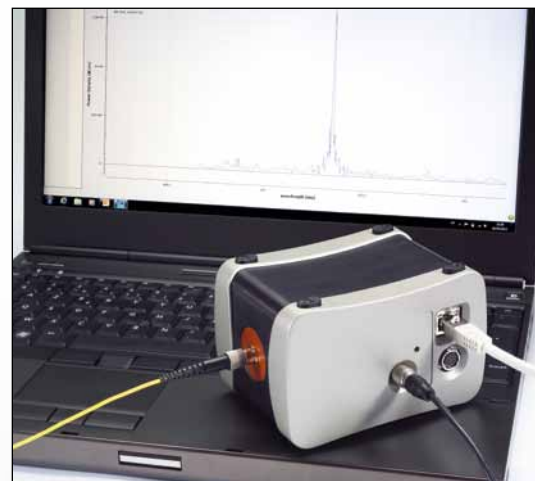
INTRODUCTION

Two major trends have emerged in the field of spectroscopy:

performance improvements to cater for a rapidly increasing number of new applications, and the quest for greater simplicity and compactness to make spectroscopy more accessible. The technologies available up until now have tended to focus on one of these two issues to the detriment of the other or, at the very least, have struggled to strike a successful balance.

SWIFTS™ TECHNOLOGY represents a new approach to spectroscopy and is the first fully-integrated solution, a step above the miniaturization efforts made over the last few years. Fundamentally, **SWIFTS™ TECHNOLOGY** is both a high-performance solution and an integrated solution, not a compromise between the two. Typically, a **SWIFTS™** chip 30 mm long (and a few mm wide) featuring the full range of spectroscopic optical detection functions will provide an ultra-high spectral resolution of 70,000, i.e., 0.005 nm at 630 nm or 0.2 cm⁻¹ or 3 GHz. This is a resolution that can only be achieved by the best high-end commercial spectrometers. Meanwhile, reaching a spectral resolution of 0.1 nm, generally described as a high resolution, only requires a 2 mm x 2 mm chip!

The **ZOOM Spectra** is the first high performance spectrometer to make use of **SWIFTS™ TECHNOLOGY**, offering access to ultra-high spectral resolution on a simultaneous bandwidth of a few nanometers, with a high frame rate.



Unlike previous ultra-high resolution spectrometers, the **ZOOM Spectra** boasts the unique ability to simultaneously offer:

- > High spectral resolution of 50,000 / 0.005 nm at 630 nm
- > Simultaneous bandwidths of 5 to 14 nm within 630–1070 nm
- > A high frame rate of up to 30 kfps
- > Very long-lasting factory calibration
- > A compact size: 8 x 8 x 12 cm
- > A trigger

Main applications:

- > Tunable laser control
- > Laser diode measurement
- > High-power laser side mode control
- > Bragg component measurement
- > High-depth OCT

Several of these applications are discussed in this White Paper.



Tunable DFB laser diode

Distributed Feedback (DFB) lasers are commonly used as tunable lasers over a range of a few nanometers. This is generally achieved by adjusting the temperature of the chip, which is monitored by a driver that also monitors the current.

This is a useful way of obtaining a tunable laser for a narrow range. However, in many applications tuning quality is critical. Unfortunately, many of the DFB lasers available on the market offer poor quality, with mode-hopping or competing modes sometimes occurring over the specified tuning range.

In the following example, we checked an 852 nm DFB laser that could be considered to be of a very high quality, but was being used over a range slightly beyond its specified operating conditions.

The scan was performed between 851.200 nm and 853.180 nm by tuning the chip temperatures between 5°C and 40°C when the ambient temperature is 24°C.

The recommended range of operating temperatures is 15°C - 40°C. The 5°C - 15°C tuning range was therefore out of specification.

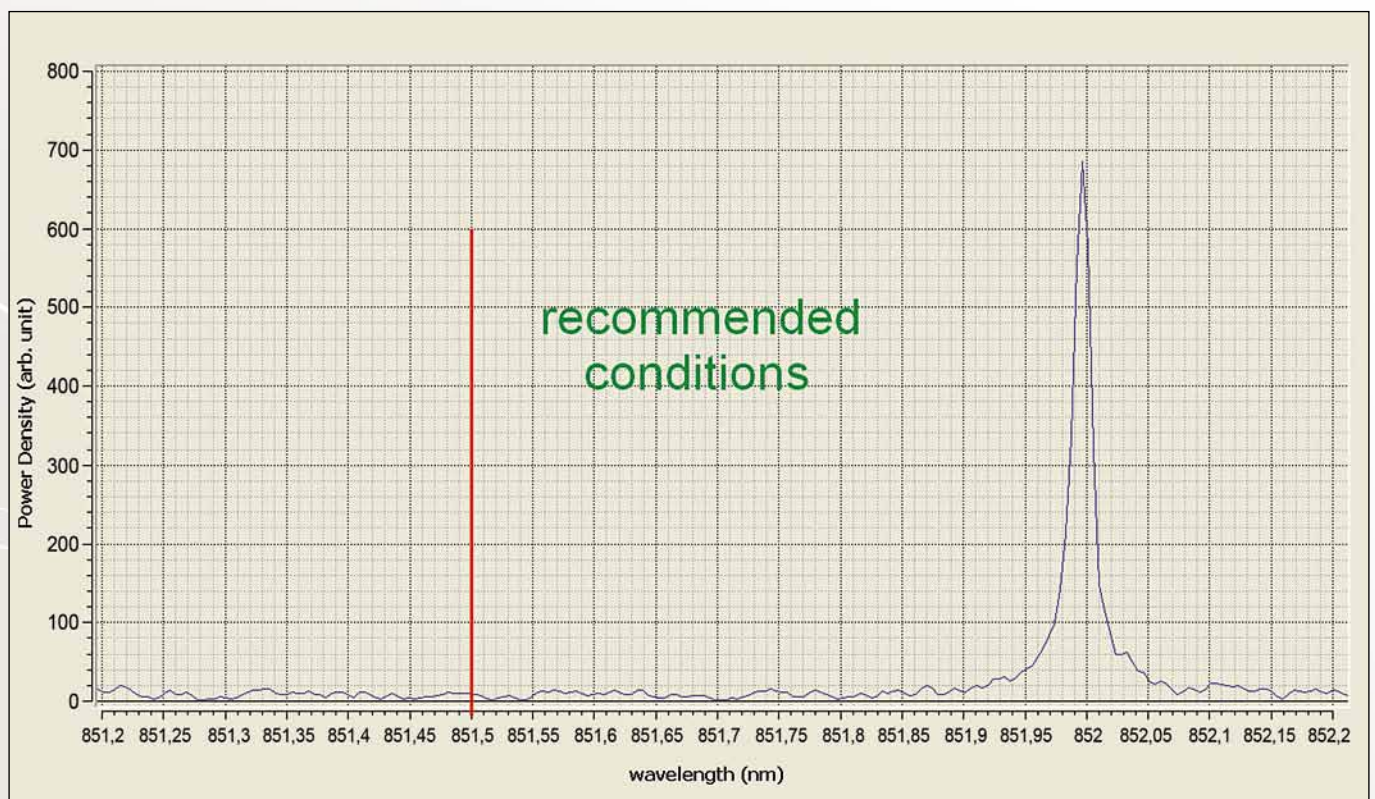


Figure 1

Measurement with the ZOOM Spectra of an 852 nm DFB laser. Forward current 140 mA
Chip temperature 20°C: within the recommended temperature limits. This is very much a single-mode laser.

The spectrum in figure 2 is the result of a low-rate measurement (100Hz) and one could deduce that there were two competing modes. However, when the measurement was performed with the **ZOOM Spectra** at a relatively high rate ($> 1,000\text{kHz}$), it could be observed that these were hopping modes that never co-existed.

The exact operating range was then determined with the same instrument used to monitor the wavelength.

Such a comprehensive analysis of the DFB laser's behavior is possible thanks to three key capabilities offered by the **ZOOM Spectra**:

- > Measurement of the true spectrum and not just the average wavelength, as is the case with a Wavelength meter
- > High spectral resolution so as to discriminate two narrow laser modes
- > High-rate measurement so as to demonstrate that the two modes never co-exist

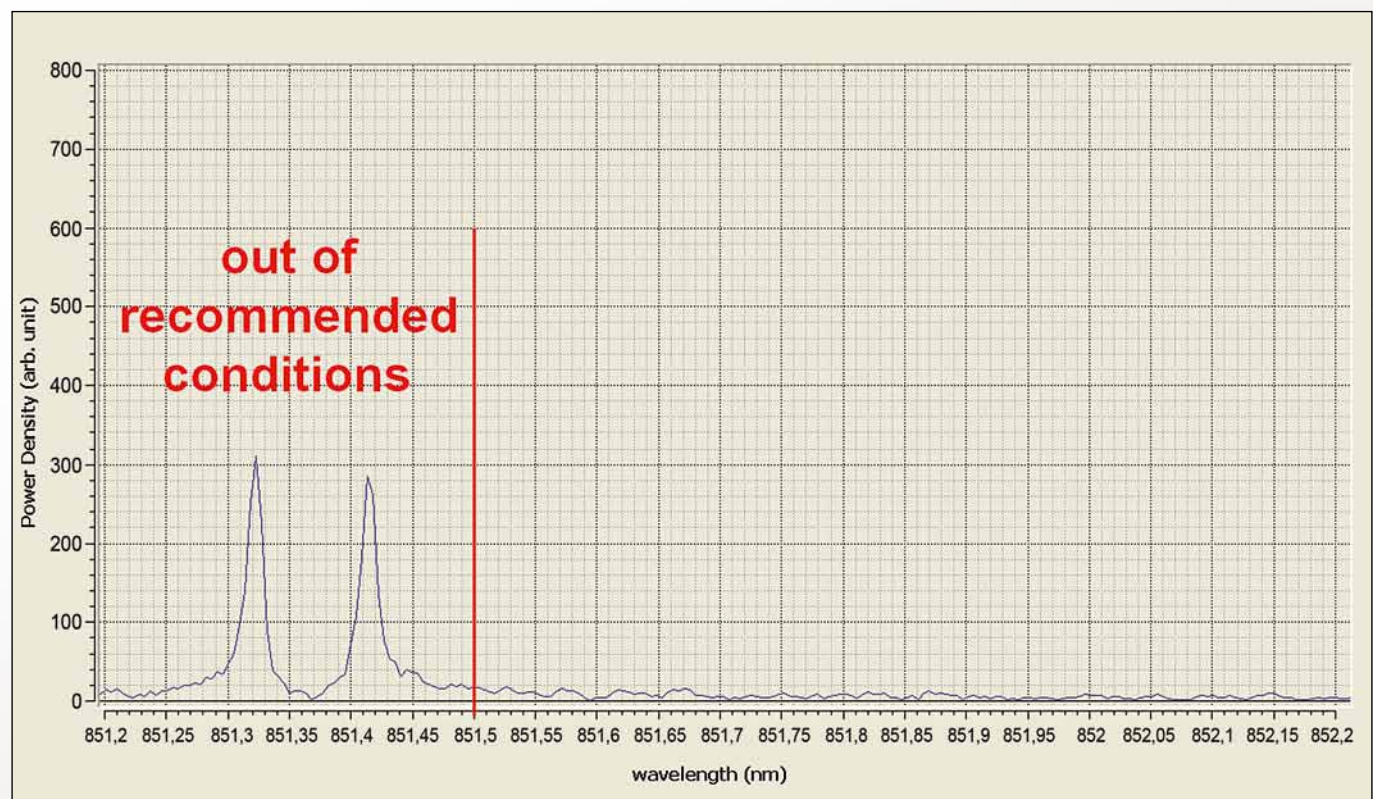


Figure 2

Low-rate measurement (100Hz) with the ZOOM Spectra of an 852 nm DFB laser.

Forward current 140 mA - Chip temperature 7.9°C: outside recommended conditions. Two modes are measured 0.094 nm apart.

Measurement of a VCSEL 850 nm transceiver

A simple VCSEL chip can emit a large number of very unstable laser modes (see figure 3). Based on VCSEL technology, the telecommunication industry has developed optical transceivers for high-speed computer and telecommunications networks that use optical fibers. The resulting emitting signal can be closely monitored and displays a spectrum comprising several selected laser beams.

A standard check involves numbering the beams and measuring the overall width of the spectrum. However this cannot be performed to a satisfactory degree using an OSA, because the latter does not offer a sufficiently high spectral resolution.

An 850 nm transceiver was measured with an OSA, a standard mini-spectrometer and the **ZOOM Spectra**. Special care was taken to scramble the different modes of the fiber. Different temperature conditions explain the wavelength variations between the different measurements.

It can be observed that the **ZOOM Spectra** alone allows discrimination of all the laser modes, thus providing a true understanding of the device. In each case, the line width of the measured spectrum is subject to the limitations of the instruments, but it is narrower in the case of the **ZOOM Spectra**, offering greater accuracy over the entire width of the spectrum.

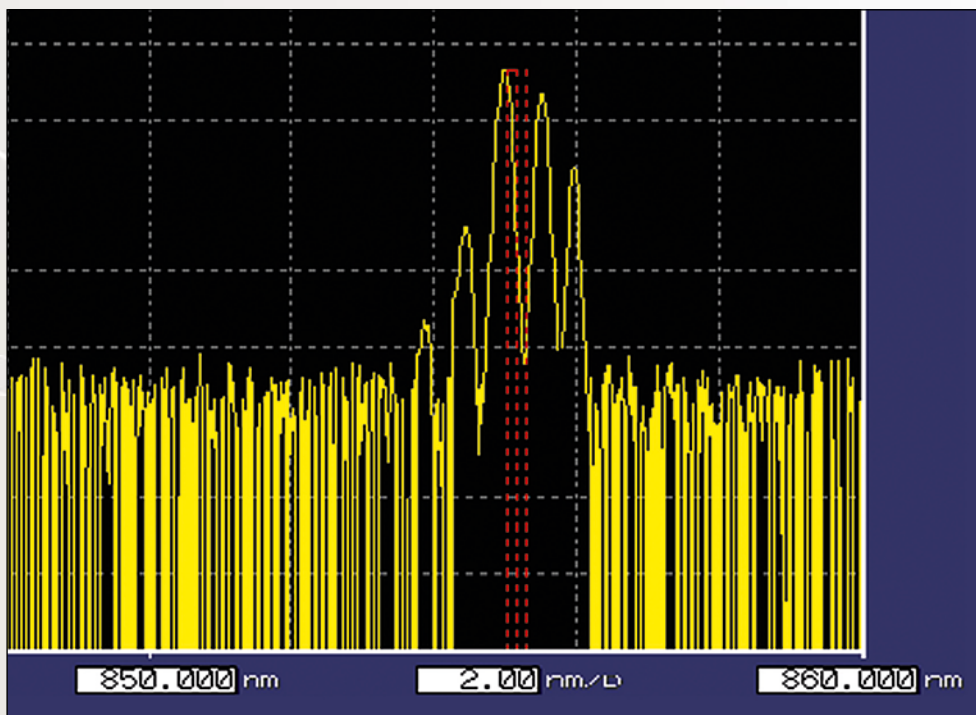


Figure 3

Measurement of an 850 nm optical transceiver with a standard Optical Spectrum Analyzer. The dynamic is very good, although not entirely necessary; the spectral resolution does not allow discrimination of all the laser modes.

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APPLICATIONS EXAMPLE 2



Figure 4
Measurement of an 850 nm optical transceiver with a high-end standard spectrometer.

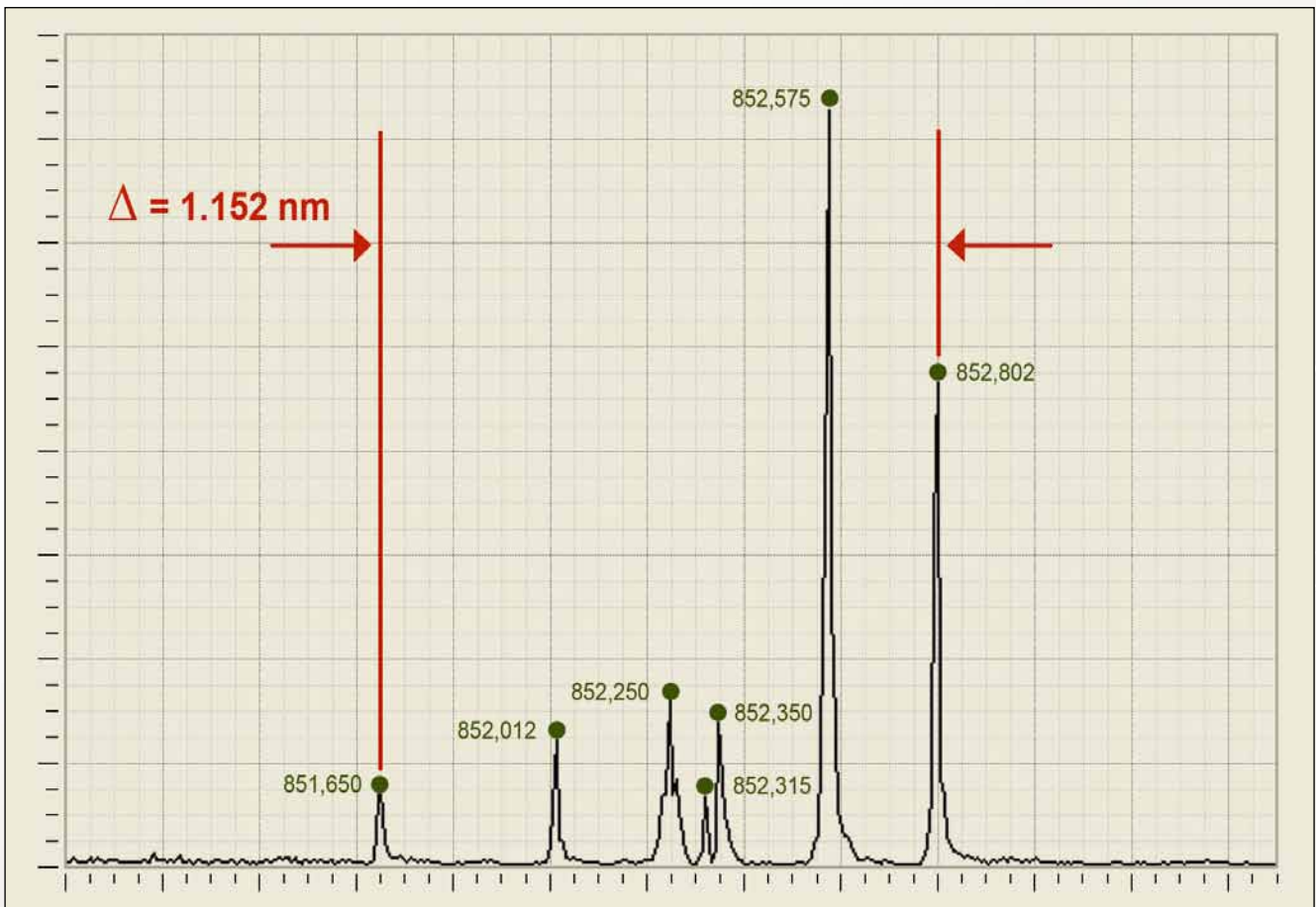


Figure 5
Measurement of an 850 nm optical transceiver with the ZOOM Spectra.

Analysis of a Raman laser at 785 nm

In Raman Spectroscopy, good knowledge of the laser spectrum that illuminates a sample is very important if the photons detected are to be interpreted accurately. Indeed, Raman spectroscopy is a non-destructive technique for the analysis of materials based on the detection of inelastically scattered photons once the sample has interacted with a monochromatic light beam. The frequency difference (Raman Shift) between excitation photons and scattered photons provides information on the chemical nature of the molecule that caused the scattering.

For this particular analytical technique, different wavelengths (and therefore different laser sources) can be used, including:

- > The UV range: 244nm (Argon), 325nm (He-Cd), 363.8nm (Ar++)
- > The Visible range: 488nm (Ar+, blue), 514nm (Ar+, green), 532nm (YAG, green), 633nm (HeNe, red)
- > The NIR range : 785nm (laser diode), 830nm (laser diode)

Or other tunable-wavelength lasers such as External Cavity Lasers.

Using the **ZOOM Spectra**, a number of laser sources were characterized at 785 nm for use on high-end Raman laboratory devices in applications such as biological analysis.

Experimental measurement

We present below the results for two different laser sources connected. The laser sources was connected to the **ZOOM Spectra** either directly with a single-mode fiber connector (FC / APC - see figure 7), or via a beam splitter and collimator, and after injection into a multimode fiber (200-micron core - see figure 6). In the latter case, a beam splitter was used to split the laser beam, part of which illuminated a sample.

The laser sources used were continuous. Spectrum acquisition was performed with the **ZOOM Spectra** at room temperature and in Continuous mode, with an integration time of between 10 and 100 ms.

Typically, the Raman lasers used featured adjustable power output, allowing the Raman effect to be measured in different types of materials. As shown in figures 6 and 7, when we varied the power of a laser there was a clear change in the laser spectra, which could potentially modify the analysis of the illuminated sample:

- > As shown in figure 6, when the laser's power was increased by a factor of 5, we observed a 0.6 nm increase in the laser emission wavelength, while remaining within a power range that was non-destructive for the materials analyzed.

In figures 6 and 7, the **ZOOM Spectra** demonstrates the occasionally multimodal nature of the lasers, with between 2 and 6-8 different wavelengths emitted.

APPLICATIONS EXAMPLE 3

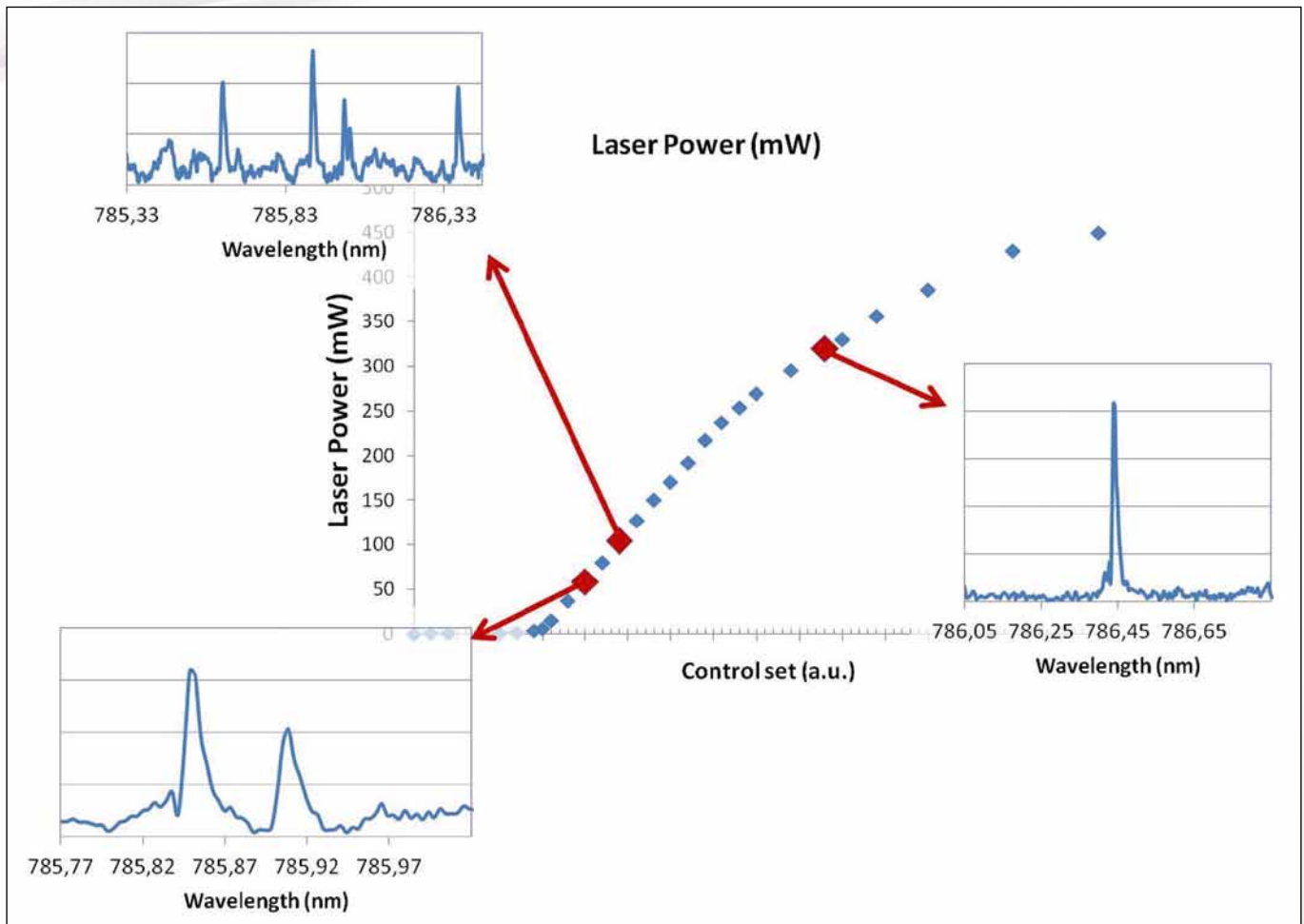


Figure 6
 Three spectra obtained over different power ranges. Connection with a multimode fiber and a collimator.

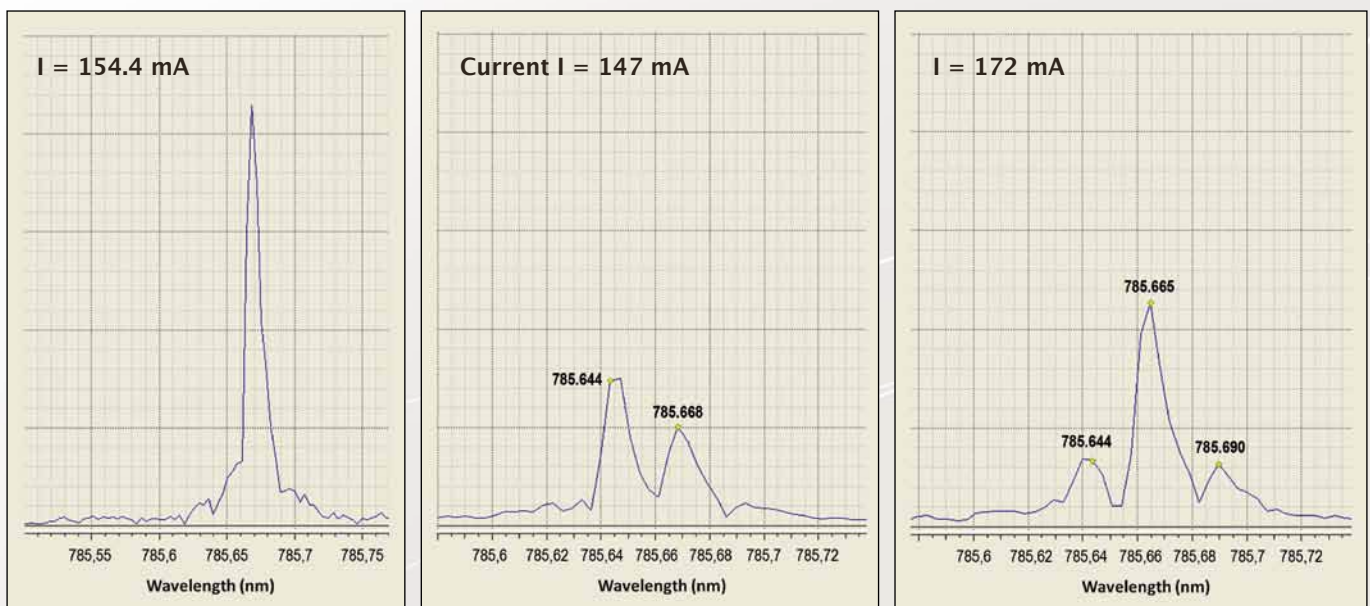


Figure 7
 Three spectra obtained over different power ranges. Connection through a single-mode fiber.

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APPLICATIONS EXAMPLE 3

In such cases, during Raman analysis, the samples are no longer irradiated by a single wavelength but several wavelengths which multiply the Raman spectra and then decrease the resolution of disturb the data processing.

The Zoom Spectra can be used to control and record the stability of the exciting laser before and during Raman analysis. The figure below present the visualization of the start-up procedure of a 785 nm DPSS laser with a customized LabVIEW visualization showing the evolution of the spectrum (including hopping modes) and the current spectrum.

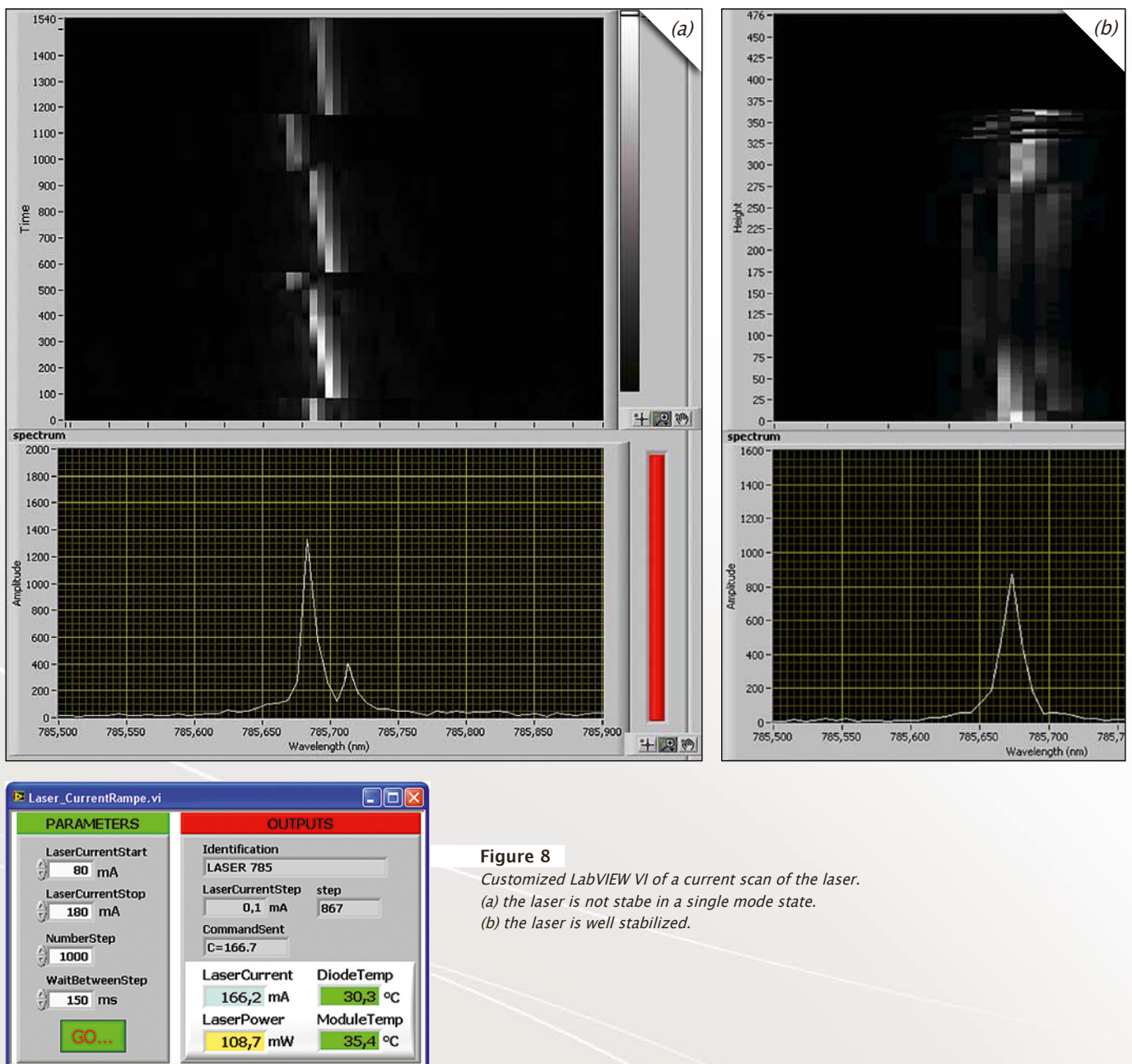


Figure 8
Customized LabVIEW VI of a current scan of the laser.
(a) the laser is not stable in a single mode state.
(b) the laser is well stabilized.

From the processing data produced by the **ZOOM Spectra** it was easy to extract the parameters required to characterize a laser in terms of its wavelength stability over time (central wavelength, FWHM width, etc.) or its intensity.

APPLICATIONS EXAMPLE 3

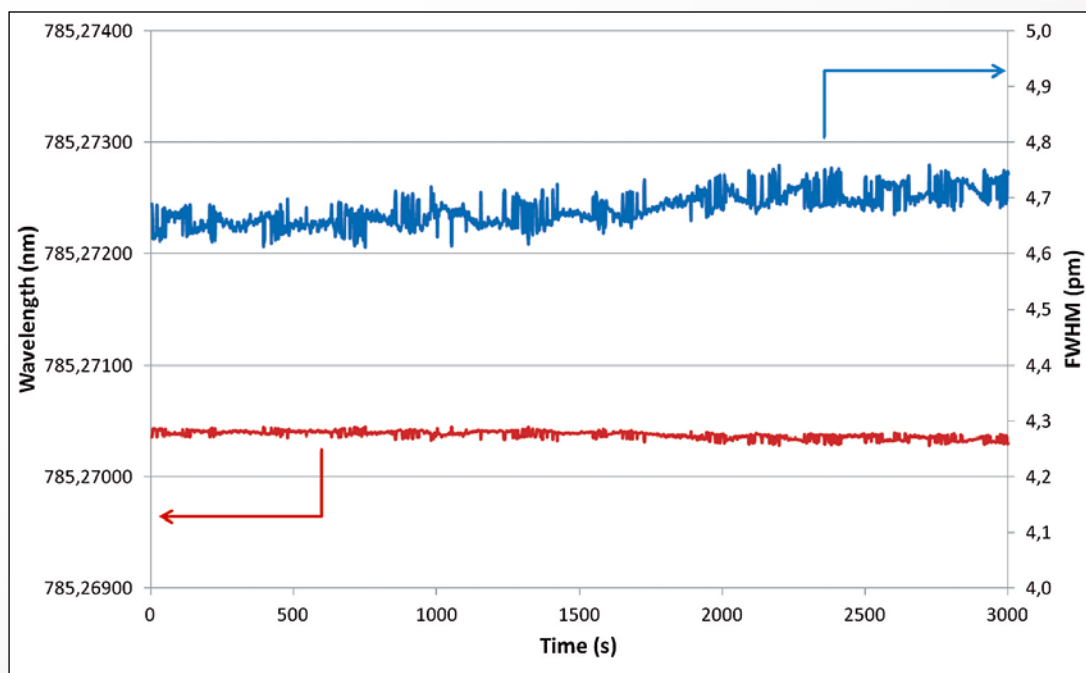
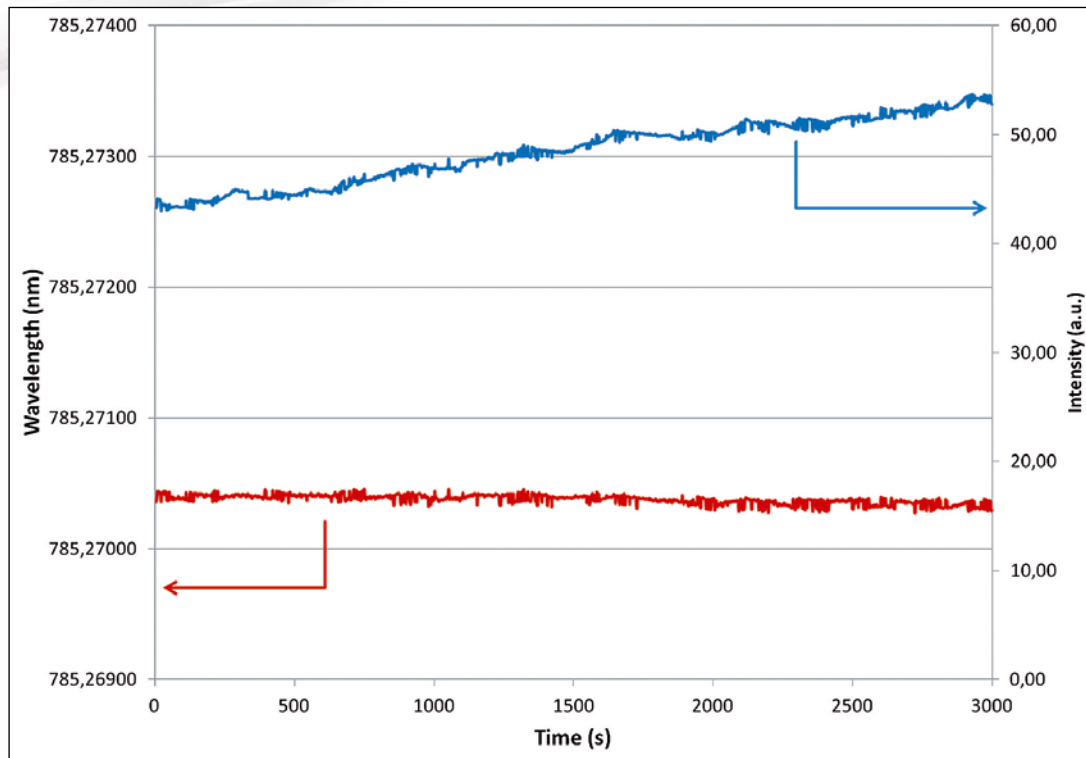


Figure 9

Evolution of a Raman laser wavelength (central wavelength and FWHM) with a pm resolution, and spectral intensity during a Raman analysis (duration: 3000s).

Using the **ZOOM Spectra**, a number of laser sources were characterized in terms of spectral stability, offering a very useful knowledge for use on high-level Raman laboratory devices. It also demonstrates the great advantage to implement the **ZOOM Spectra** in a Raman setup for online monitoring.

Control of the stability of high power laser (Nd-YAG, Nd-YLF)

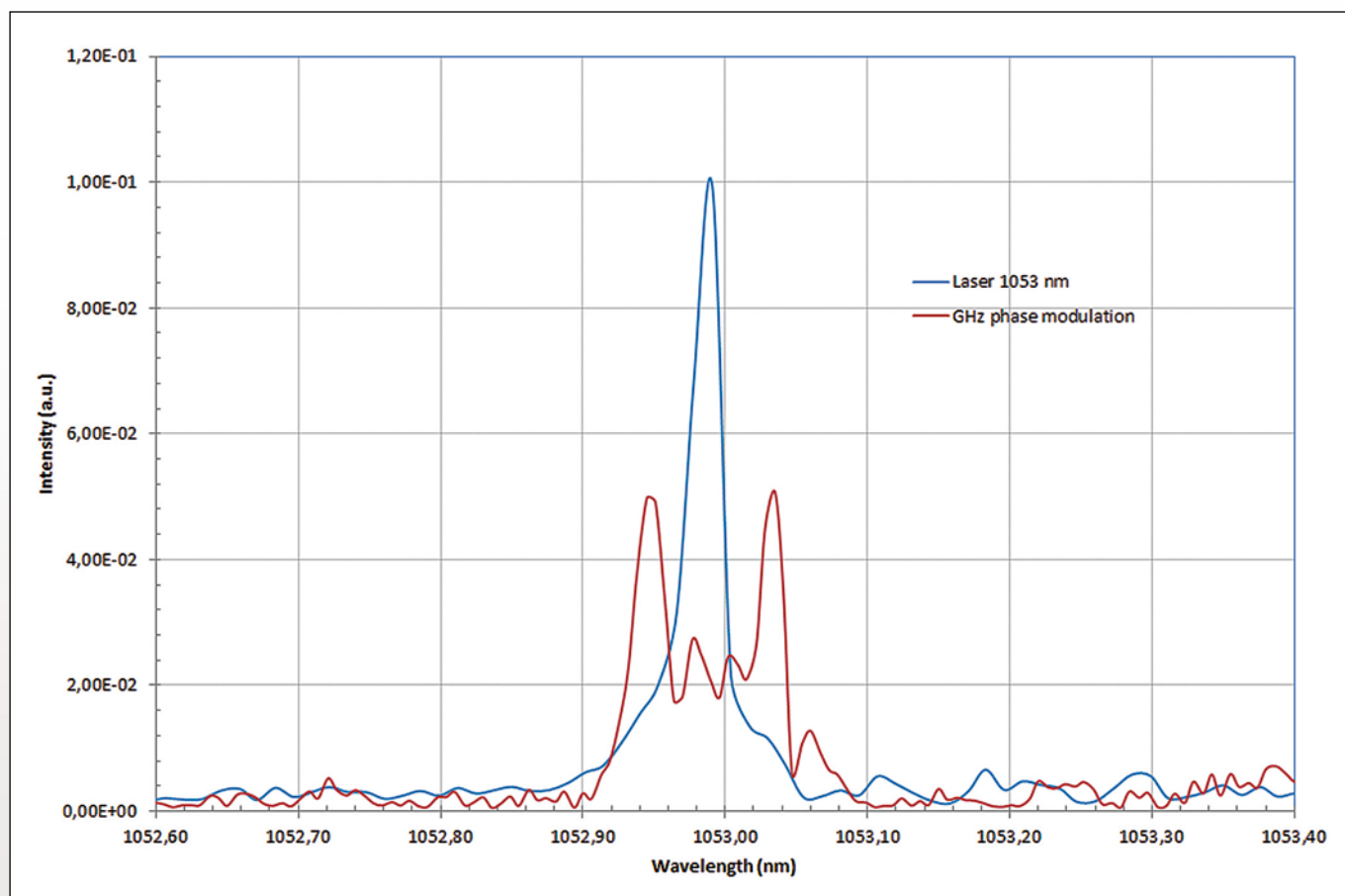


Figure 10
1053 nm Nd-YLF laser measurement and with GHz phase modulation.

APPLICATIONS EXAMPLE 4

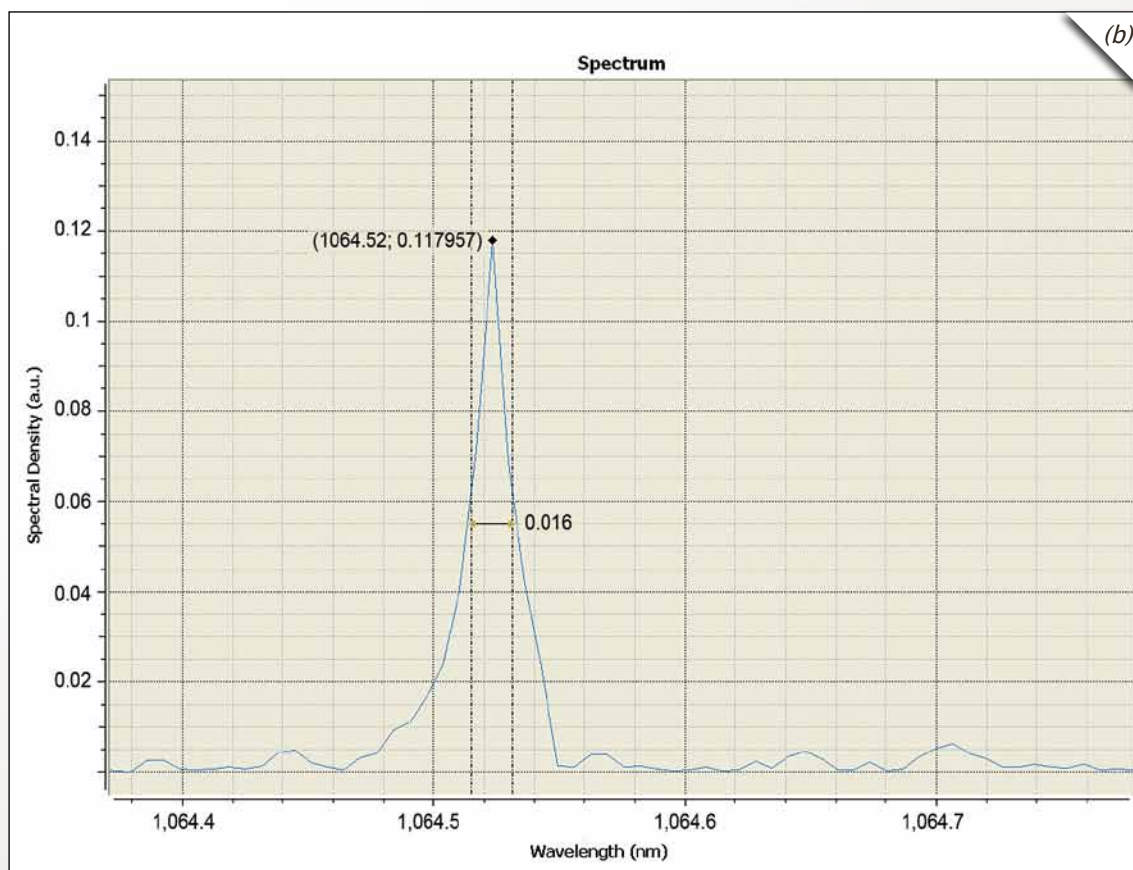
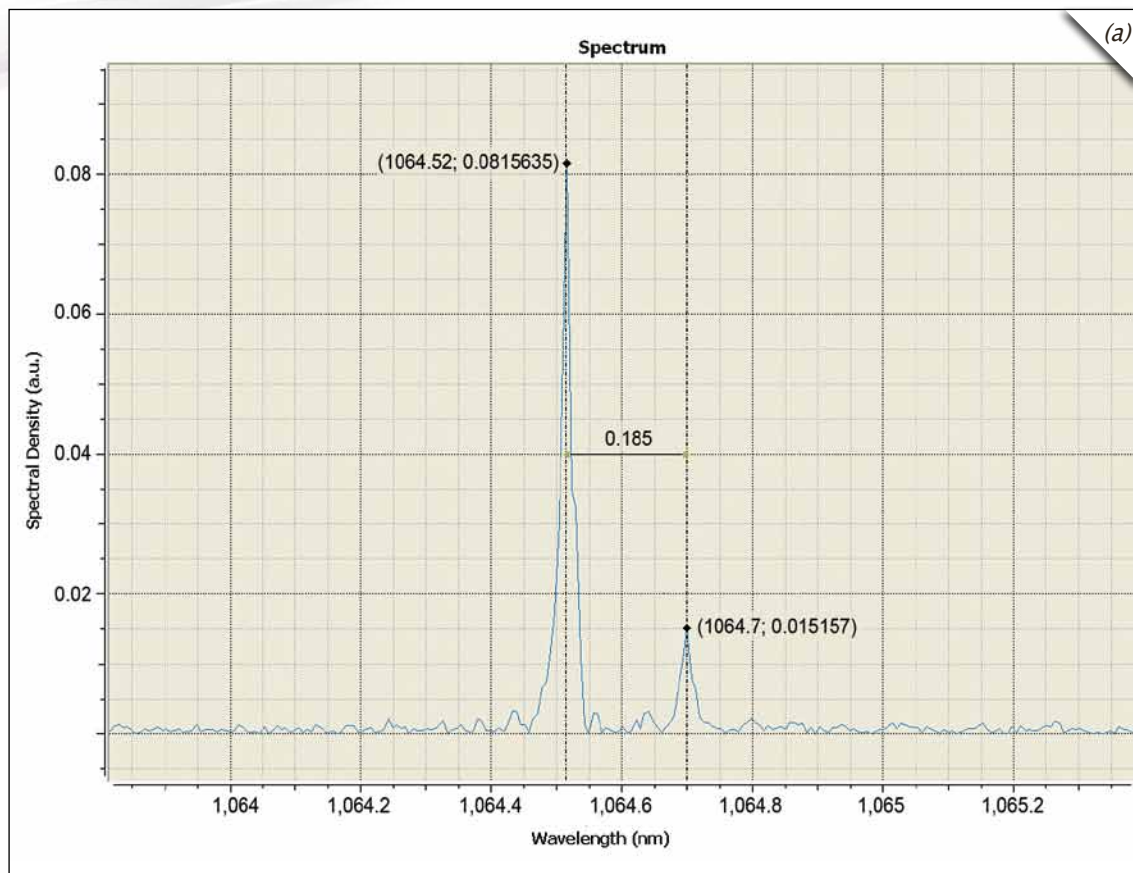


Figure 11
1064 nm Nd-YAG measurement visualized with the Spectra Resolver software.

(a) The ZOOM Spectra detect a side mode in particular laser operating conditions.

(b) Measurement of the linewidth (0.018 nm).

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High-depth Optical Coherent Tomography

By Fabrice THOMAS, Resolution Spectra Systems

As an **interferometric system**, the SWIFTS-based spectrometer intrinsically offers very useful OCT capabilities. A simple test to assess the quality of OPD (Optical Path Difference) measurement was conducted by the IPAG Laboratory using a Labview interface.

The setup was as follows: a Michelson interferometer with one mobile arm offering 4 mm of amplitude in 2 nm steps; a filtered SLED emitting at 852nm +/- 5 nm as the source, the aim being to obtain an interferogram of 2 pixels FWHM in each sampling element; the **ZOOM Spectra** product, which can measure a maximum OPD of 40 mm in air with no moving parts. TE polarization alone was selected.

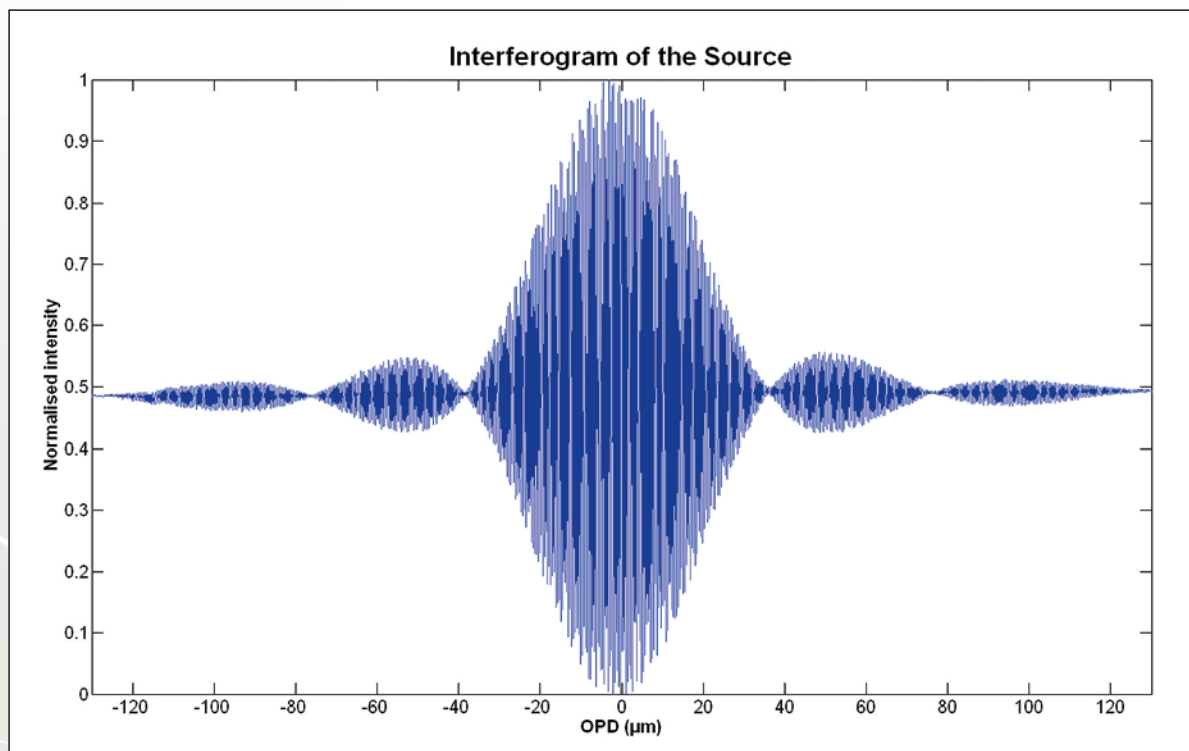


Figure 12

Interferogram of the source, a filtered SLED emitting at 852nm +/- 5 nm.

An OPD scan in OCT mode was produced over a range of 4 mm at 30 kiloframes per second. The scan was limited to a 4 mm scan range because of the OPD setup, but could have been continued up to 40 mm with good results up to the limit corresponding to the source's spatial coherence.

As shown in figure 13, the spatial resolution is around 20 µm (FWHM in air) with a positioning accuracy of around 2 µm.

APPLICATIONS EXAMPLE 5

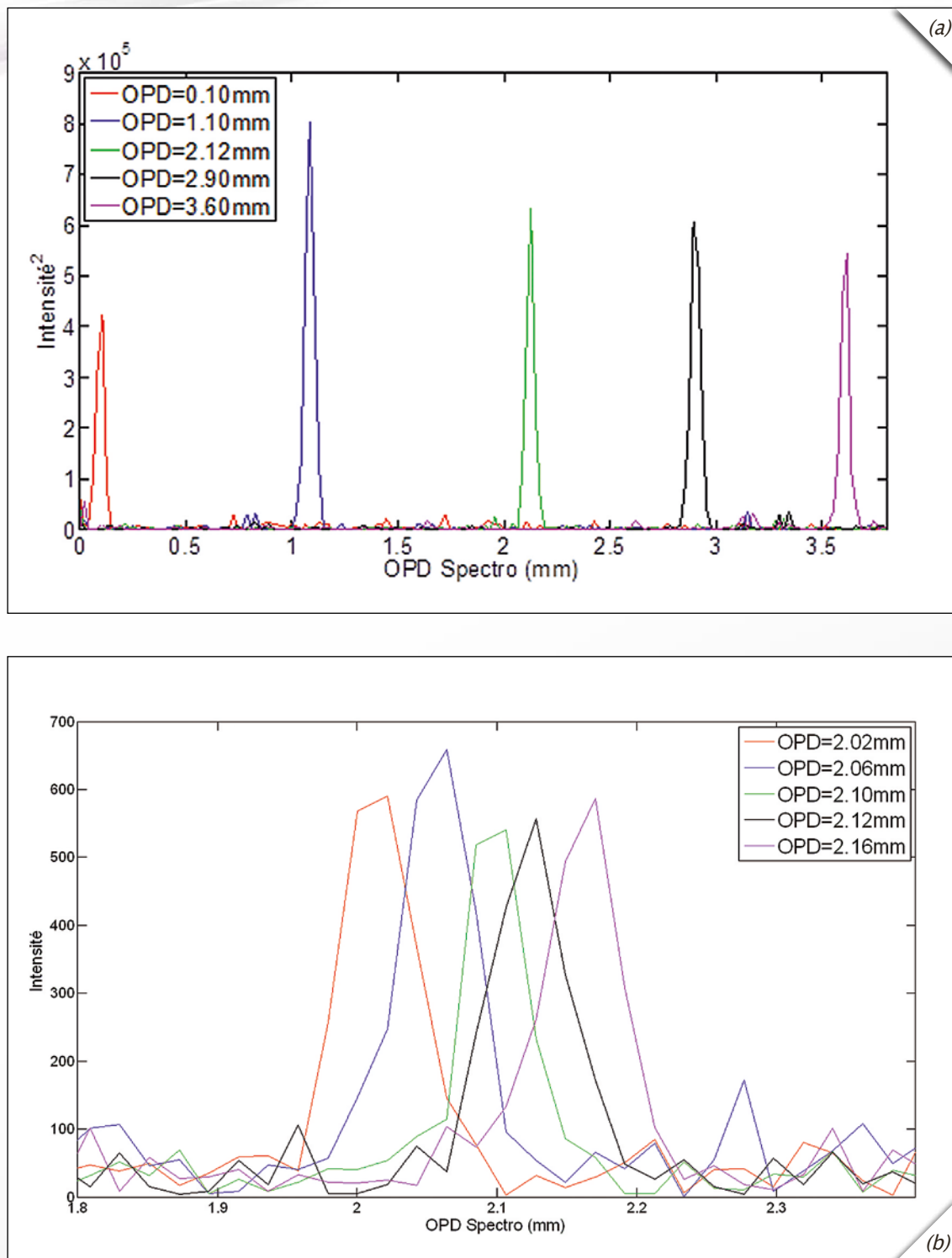


Figure 13

OPD scan measured with the ZOOM Spectra. (a) a few positions of the scanning mirror across the entire 4 mm range. (b) a few narrow positions of the scanning mirror to illustrate the resolution.

To sum up, the **ZOOM Spectra** can be used as a very high-performance sub-system for high-depth OCT in various industrial or research applications. Contact us for more information.

Spectrum of a Fabry–Perot cavity

comprising two Fiber Bragg Gratings centered at 851.7 nm and spaced 8mm apart, obtained with the ZOOM Spectra

By Mikhael de Mengin Poirier, IPAG, Université Joseph FOURIER – Grenoble, France

1. Setup

We wanted to measure, as accurately as possible, the spectrum of a Bragg grating Fabry–Perot cavity structure centered at 851.7 nm and with an FWHM of approximately 300 pm. To do so, we designed the following setup.

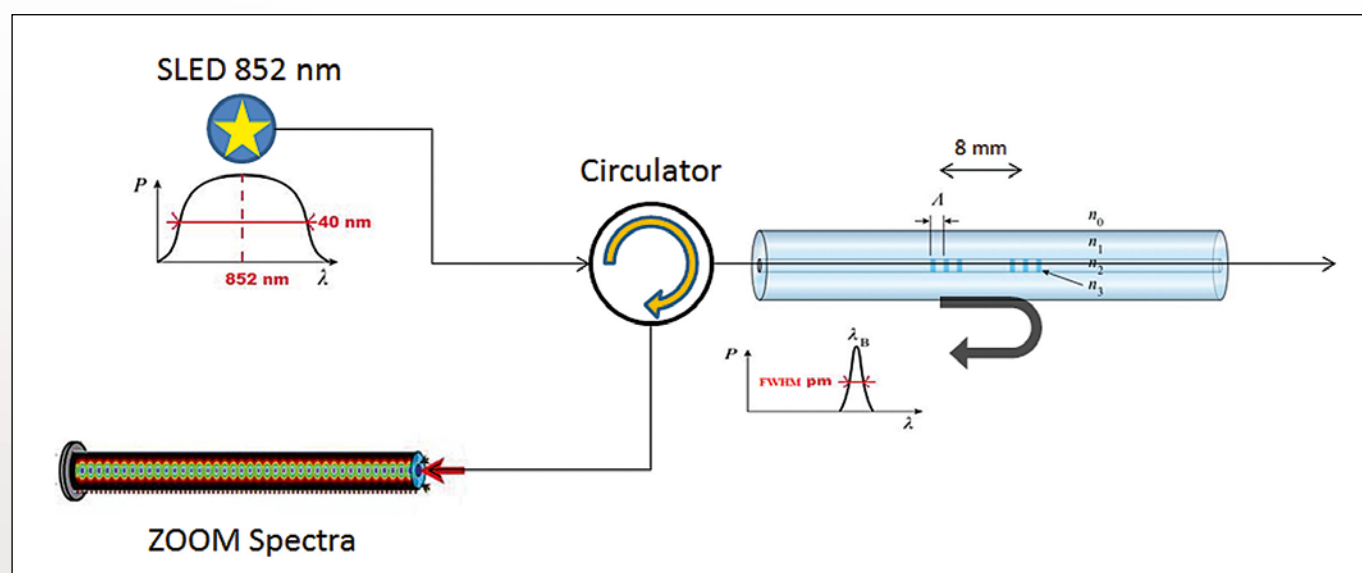


Figure 14
Test setup of Fabry–Perot cavity between two Fiber Bragg Gratings.

a. Source

- > Superluminescent Light Emitting Diode (SLED)
 - Center wavelength: 852 nm
 - 40 nm FWHM

b. Spectrometers

- > ZOOM Spectra spectrometer by Resolution Spectra Systems
 - 0.01 nm Optical Spectral Resolution (FWHM)
 - 630 – 1070 nm range

c. Bragg Grating Fiber

- > GFPC designed by IXFiber
 - Center wavelength: 851.71 nm
 - 310 pm FWHM
 - Peak Reflectivity: 89.9 %
 - Physical size of the Bragg sensor: 8 mm

APPLICATIONS EXAMPLE 6

Below are the specifications of the fiber Bragg grating Fabry-Perot cavity structure:

Fiber type	HI780
Recoat	acrylate 280 μm
Pigtail 1 length	1 meter
Pigtail 2 length	1 meter
Connectors	FC-APC/none

Parameter	Specifications	Measured
Center Wavelength (nm)	851.5 +/-0.5	851.71
FWHM Bandwidth (nm) @ - 3 db	about 0.3	0.31
Peak Reflectivity (%)	85 +/-5	89.9
Proof test (kpsi)		100
Polarization axis alignment		N/A

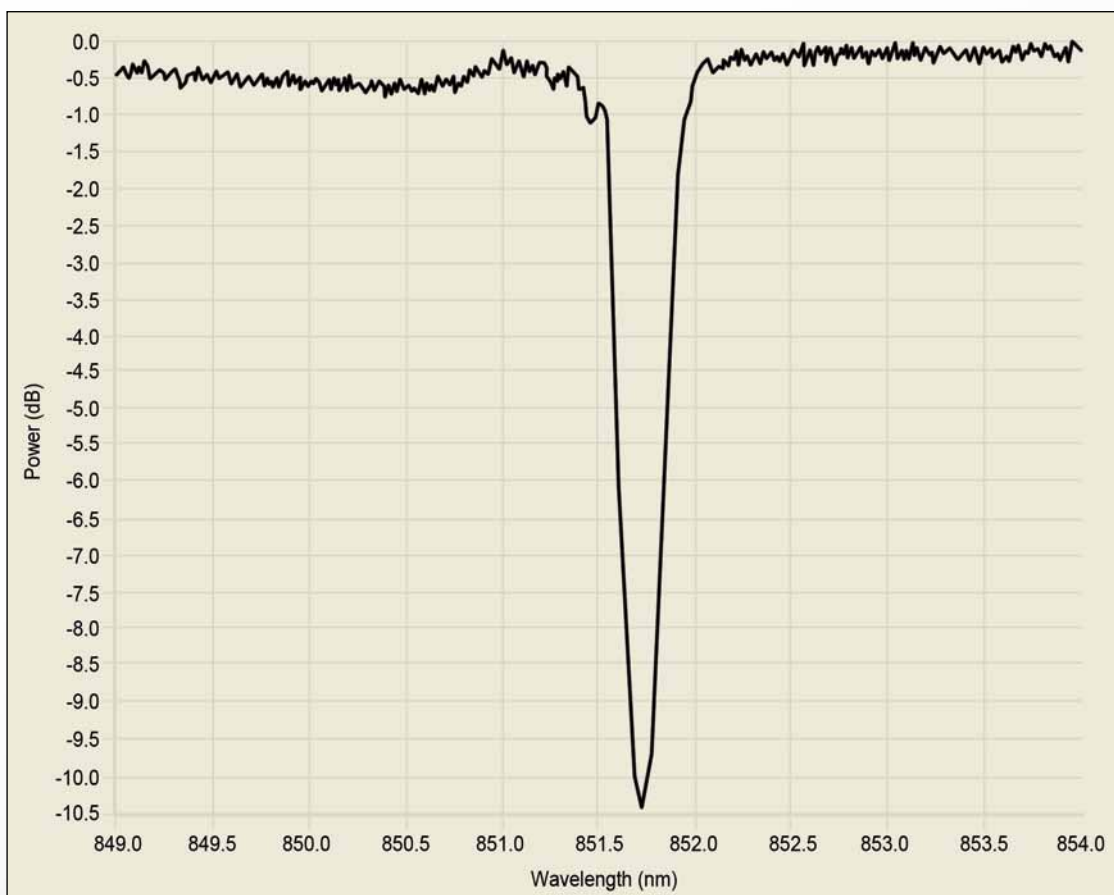


Figure 15
Fiber Bragg Grating profile.

The light emitted by the SLED was reflected by the GFPC using an FC/PC circulator and received by the spectrometer. We added a polarization device to reduce disturbances relating to the polarization wavering caused by the Bragg fiber's different settings. Secondly we protected the Bragg grating with a thin piece of aluminum foil to reduce the effect of room-temperature variations near the fiber.

2. Measurements

Using the **ZOOM Spectra** spectrometer, we measured the spectra reflected. To highlight the GFPC's precise spectrum, we decided to apply a certain amount of strain to the Bragg grating. This resulted in a shift in the center wavelength of the spectrum, because the wavelength of the spectrum's central peak varies in proportion to strain or temperature. If we consider the spectrum with no applied strain by way of a reference, we can deduce the following relative spectrum.

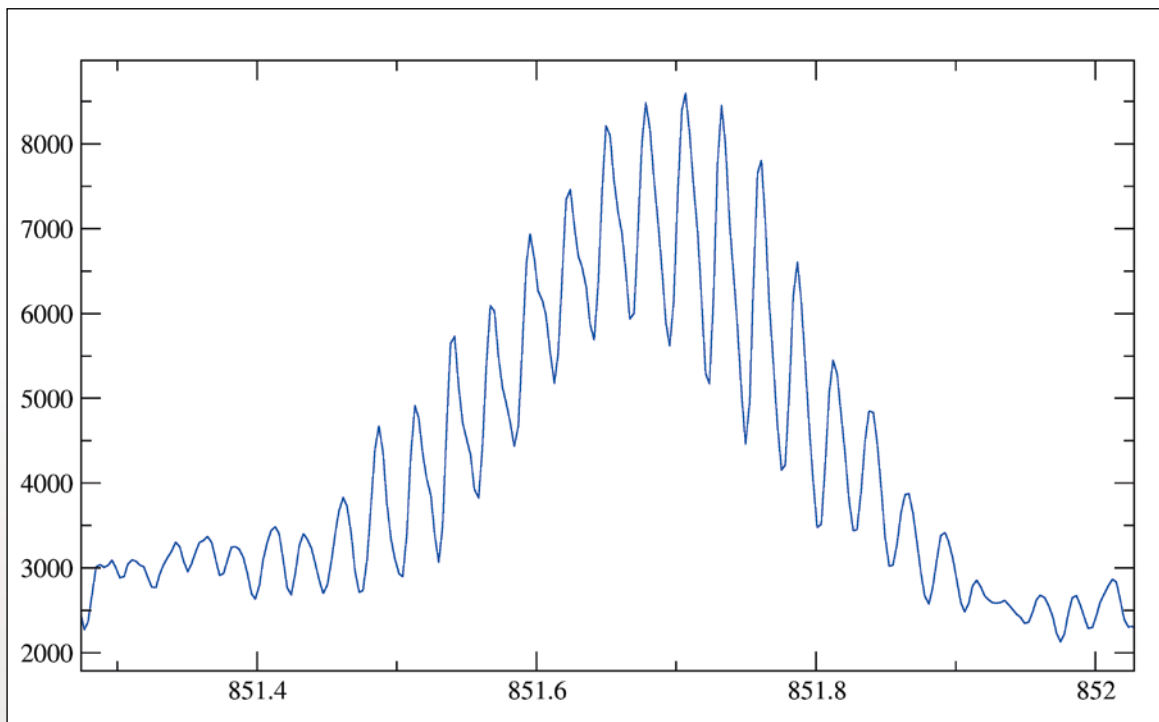
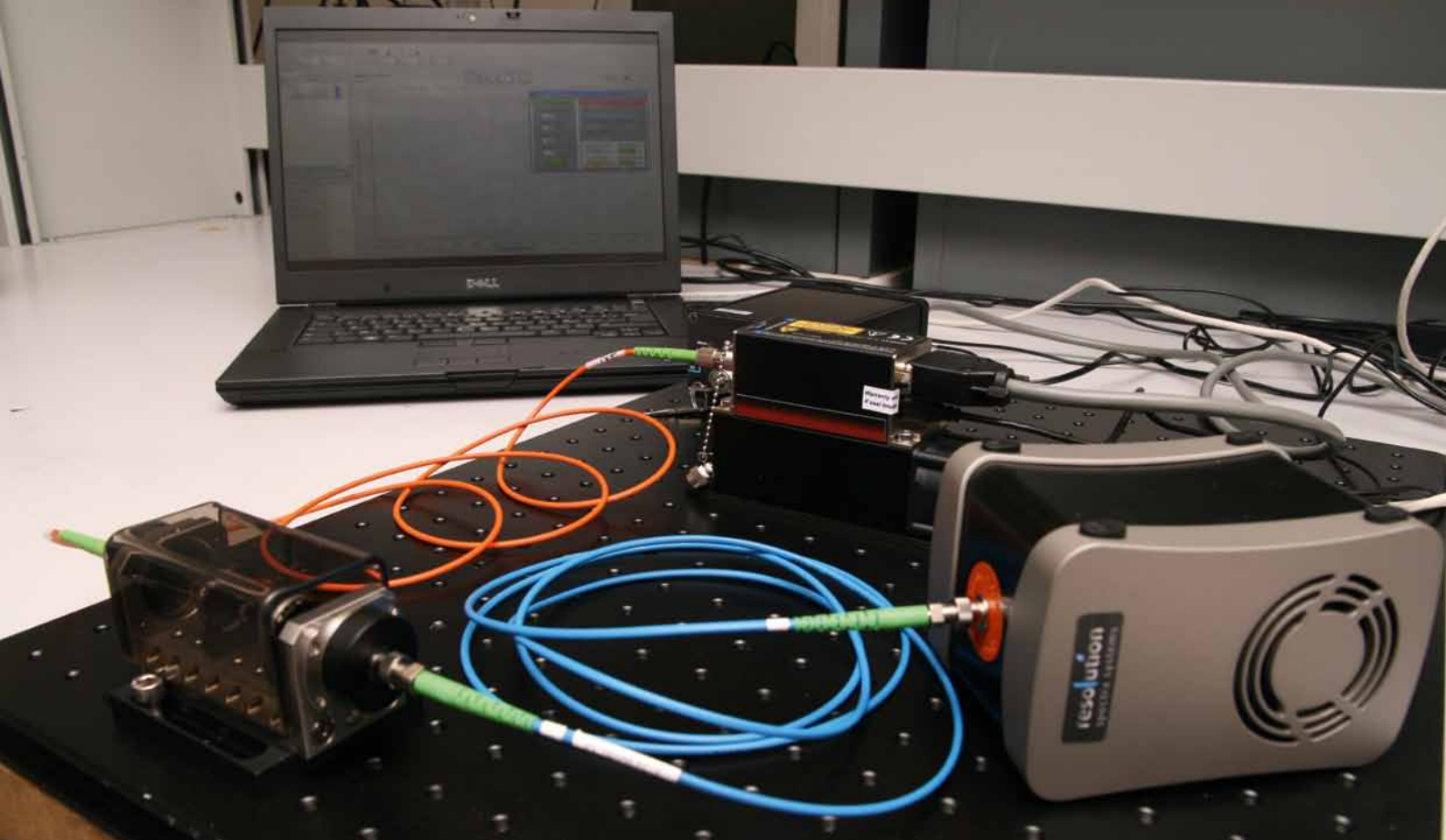


Figure 16
Reflected spectra - Global FWHM: 0.280 nm - Central wavelength: 851.72 nm.

3. Conclusion on the measurements

Through barycentric measurement, we were able to deduce that the center wavelength of the spectrum was at 851.72. The FWHM was measured at 280 pm. The advantage of this measurement was not only its ability to measure the overall spectrum more accurately but also its ability to see the inner peaks. Indeed, thanks to its high resolution, the **ZOOM Spectra** spectrometer allows us to measure the inner peaks and to improve on Fiber's imaging feature. Only a spectrometer with such a high resolution can discriminate the inner peaks (13.5 pm FWHM) from the envelope.



FREQUENTLY ASKED QUESTIONS ABOUT THE ZOOM SPECTRA HIGH-RESOLUTION HIGH-RATE SPECTROMETER

About the technology

What SWIFTS™ technology is used in the ZOOM Spectra?

- > This patented technology was invented by scientists of Joseph Fourier University and the Institut National Polytechnique in Grenoble. It is based on the Nobel Prize-winning discovery made by Gabriel Lippmann at the beginning of the 20th century, which allowed the first color photographs to be produced. **SWIFTS™** stands for Stationary Wave Interferometer Fourier Transform Spectrometer. Resolution Spectra Systems holds an exclusive license for this technology.

What technologies are incorporated into the ZOOM Spectra?

- > The **ZOOM Spectra** is an implementation of **SWIFTS™** TECHNOLOGY based on a high-end linear CCD, integrated silica optics, nanotechnologies and specific algorithms. A GIGE Ethernet protocol is used for control and data communication purposes. In addition, the **ZOOM Spectra** is calibrated using a highly specific proprietary process.

How can such a high spectral resolution be achieved in a system so compact?

- > See the Nature Photonics publication on the following pages.

Are there any mobile parts inside the ZOOM Spectra?

- > No. There are no mobile parts and the core of the technology is integrated into a single component. **SWIFTS™** - based spectrometers are related to Static Fourier Transform Spectrometer family.

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FREQUENTLY ASKED QUESTIONS

ABOUT THE ZOOM SPECTRA

HIGH-RESOLUTION HIGH-RATE SPECTROMETER

About the ZOOM Spectra's performance

The bandwidth for one simultaneous measurement is specified to 5 - 14 nm. Can I simply use my ZOOM Spectra on a bandwidth range of 5 to 14 nm? How are the different calibration bands determined?

> Because the **ZOOM Spectra** is a Fourier Transform Spectrometer, the consequence of discretization (signal sampling) is the restriction of the spectral bandwidth. The bandwidth of each band of the ZOOM Spectra is directly linked to the Shannon criterion. The **ZOOM Spectra**'s sampling performance is such that the spectral bandwidth is around $11,748 \text{ cm}^{-1}$, i.e. 5 nm at 630 nm or 14 nm at 1070 nm.

The **ZOOM Spectra** can be calibrated on every band within the detection range on the same hardware device. Data processing is performed taking into account the effective spectral window between two spectral aliasings.

Therefore, the user only has to select the calibrated spectral band in which the spectrum is measured in order to perform the appropriate data processing.

What do you mean by high-resolution?

> We define spectral resolution as the full-width at half-maximum (FWHM) of its response to perfectly monochromatic radiation. It is the minimum spectral width $\delta\lambda$ (wavelength), $\delta\sigma$ (wavenumber) or $\delta\nu$ (frequency) that the instrument can isolate.

One may prefer to characterize the spectrometer using a dimensionless magnitude, i.e., the resolving power R:

$$R = \lambda / \delta\lambda = \sigma / \delta\sigma = \nu / \delta\nu$$

where $\delta\lambda$ is the smallest difference in wavelength that can be distinguished at wavelength λ .

By high resolution we mean a typical resolving power of a few tens of thousands, i.e., a few picometers.

What is the difference between absolute accuracy and resolution?

> Sometimes, the term "resolution" is used incorrectly to mean absolute accuracy, which is the maximum absolute wavelength error that can be measured at the central wavelength of a spectrum peak.

What is the spectrometer's Signal-to-Noise Ratio?

> For a given measurement, we define the Signal-to-Noise Ratio (SNR) of the **ZOOM Spectra** spectrometer as the ratio between the maximum intensity of the spectrum and the maximum noise intensity.

In reality, it is rather difficult to provide a generic specification for the SNR, because it will depend on the exact signal and measurement parameter settings used.

Since the **ZOOM Spectra** detects a signal other than the direct spectrum, the camera's SNR is a separate characteristic of the instrument. The link between the camera's SNR (signal detected) and the spectrometer's SNR (obtained after signal processing) is not direct. See the explanation in the next question.

The SNR can be improved through multiple acquisition and averaging.

FREQUENTLY ASKED QUESTIONS

ABOUT THE ZOOM SPECTRA HIGH-RESOLUTION HIGH-RATE SPECTROMETER

What causes noise in the spectrum?

- > Noise in the spectrum is caused by detector and electronic noise, shot noise, which is dependent on the signal level, as well as data processing noise, which is linked to calibration accuracy and the limitations of the algorithms. It results in overall noise that is not white, i.e., a random signal with a flat power spectral density. Its intensity is partly proportional to the useful signal level. Therefore, the noise level cannot be used to directly deduce the spectrometer's sensitivity, which is defined as the minimum signal level that can be measured with an SNR higher than 1:1.

What measurement conditions correspond to the sensitivity specified, namely the input power range?

- > On the datasheet, the minimum specified input power corresponds to a measurement performed using a single-mode laser with a 10 ms integration time (digital gain of 0 dB).

The maximum input power corresponds to a measurement performed using a single-mode laser with a 320 ns integration time (digital gain of -24dB).

How is the maximum specified integration time defined?

- > The maximum specified integration time in the datasheet is the integration time for which the dark signal is about half of the full well capacity of the detector pixels, at 24°C. It is considered as a formal limit that governs the ability to perform a measurement. However, this limit can be increased by lowering the ambient temperature (it is approximately doubled with every 8° lost). Spectra Resolver Software allows a maximum integration time of about 2 s.

Is calibration dependent on temperature conditions?

- > No. Factory calibration takes into account variations in operating conditions. During measurements, the device's temperature is also measured and taken into account in data processing.

For how long is your calibration valid?

- > There are no mobile parts and the only significant change in any of the device's characteristics is in the dark noise level of the CCD, which will not change significantly within many years. The calibration will remain valid for a considerable length of time.
- > We have never experienced any deviation in the **ZOOM Spectra's** calibration.

About applications

Can I use the ZOOM Spectra to measure a pulsed laser? Up to what rate?

- > Yes. The **ZOOM Spectra** includes a trigger with a comprehensive set of modes. Consult the User Manual for further details. The spectrometer can perform measurements at a rate of up to 30,000 frames per second. If the laser pulse rate is over this limit, a strategy can be devised to enable optimized measurement (use of a pulse generator).

FREQUENTLY ASKED QUESTIONS

ABOUT THE ZOOM SPECTRA HIGH-RESOLUTION HIGH-RATE SPECTROMETER

What are the advantages of using the trigger mode?

- > The trigger has three main advantages: 1) it allows a single pulse to be measured, rather than the average of several pulses; 2) it restricts integration to the duration of the pulse, which optimizes dark noise; 3) it allows the pulse to be caught when the integration time is very small with respect to the pulse period.

How efficiently will the Zoom Spectra couple with my setup?

- > You will need to consider that the **ZOOM Spectra's** input (input connector) is a single-mode fiber with a numerical aperture (N.A.) of around 0.11 and a mode diameter of around 5 μm .

Secondly, it should be noted that the energy delivered by most laser sources is greater than the **ZOOM Spectra's** maximum power input.

In your setup, several cases may occur:

Laser free beam: If you decide to position the input fiber of the spectrometer directly into the free beam, the coupling efficiency will be roughly equal to the ratio between the fiber mode's surface area (diameter $\sim 5\mu\text{m}$) and the beam diameter (\sim FWHM of the waist). It may well be sufficient in many cases. ; Otherwise, we can propose a set of beam collimator solutions depending of your setup.

Single-mode fiber output: it can also be connected directly to the input fiber of the spectrometer. The coupling efficiency will be equal to that of the fiber connection, i.e., an approximate 0.2dB loss.

Multimode-fiber output: in this case, it is important to know whether the different fiber modes have exactly the same spectrum (from a photometric point of view). If so, you should couple one of the modes of the multimode fiber with the single-mode fiber. If not, it is essential that you perform thorough spectral scrambling on your modes. In any case, in order to stabilize the energy coupled, you will need to scramble the modes of the multimode fiber spatially and/or temporally. We can offer various scrambling solutions depending on your setup.

Other: if your setup is based on another configuration, the first step will be to perform a full photometric calculation to determine the best way of coupling your setup with the single-mode fiber. Note that in many cases, and whenever possible, you should choose a configuration that uses single-mode fibers or components.

The **ZOOM Spectra** is not suited to low-light applications. These will be addressed by another product developed by Resolution Spectra Systems.

What are the advantages of this ultra-high spectral resolution?

- > Ultra-high spectra resolution, i.e., a few picometers in the visible-NIR range, is a resolution that makes it possible to discriminate almost all visible and NIR photon emissions produced by an electronic transition in a given material, or to discriminate all laser amplification modes, from large-cavity lasers to VCSELs, for instance.

Laser modes: the frequency difference between two consecutive modes is $\Delta f = c/(2L)$, where L is the cavity length and c is the speed of light in the laser cavity. In a large cavity measuring around 6 cm, two side modes will be 9 pm apart.

FREQUENTLY ASKED QUESTIONS

ABOUT THE ZOOM SPECTRA

HIGH-RESOLUTION HIGH-RATE SPECTROMETER

What are the advantages of high-rate measurement?

- > High-rate measurement can be beneficial in three different ways:

It allows measurement averaging to be performed within a reasonable timeframe, so as to increase the signal-to-noise ratio.

High-speed phenomena can be time resolved. For instance, this is true in the case of hopping modes in lasers, which can hop at a high frequency and be identified as competing modes when using a low-rate spectrometer.

Another advantage of high-rate measurement is, of course, the ability to trigger high-pulse-rate lasers.

What is the consequence of polarizing the light analyzed?

- > To perform a successful measurement, the polarization of the analyzed light should be in TE mode (locked to PM slow axis). Otherwise, the spectrum data might be distorted and the resolution might be degraded.

Can I install my ZOOM Spectra in a rack?

- > Yes. The **ZOOM Spectra** is compatible with a 2U rack. The unit can be clamped to the rack via its baseplate and using the screw holes that can be accessed by removing the two gray covers.

Comparison with other systems

What are the advantages of SWIFTSTM technology compared to dispersive spectrometers?

- > **SWIFTSTM TECHNOLOGY** displays similar advantages to the Fourier Transform Interferometer Spectrometer, added to the advantages of a system with no moving parts and a configuration that is particularly well suited to high spectral resolution.

An interferometer spectrometer has several basic advantages compared to a standard dispersive instrument. These advantages are:

The Multiplex advantage (Fellgett's advantage), which is derived from the fact that an interferometer measures wavelengths simultaneously/with the same elements of the detector, whereas a dispersive spectrometer measures them successively (true in the case of monochromators) or on separate pixels (sensor array configuration). Unlike monochromators, **SWIFTSTM**-based spectrometers can collect a complete spectrum very rapidly. A large number of scans can be averaged in the time it takes a monochromator to complete a single scan.

Furthermore, Fellgett's advantage also states that when collecting a spectrum whose measurement noise is dominated by detector noise (which can be true of line spectra), a multiplex spectrometer such as a Fourier Transform Spectrometer will produce a relative improvement in the signal-to-noise ratio, with respect to an equivalent scanning monochromator, that is approximately equal to the square root of the number of sample points comprising the spectrum (i.e., a factor of around 40 for the **ZOOM Spectra**).

FREQUENTLY ASKED QUESTIONS

ABOUT THE ZOOM SPECTRA

HIGH-RESOLUTION HIGH-RATE SPECTROMETER

The Connes advantage states that the wavenumber scale of an interferometer, derived from a HeNe (helium neon) laser, is a great deal more accurate and boasts much greater long-term stability than the calibration of dispersive instruments.

Because of the way in which the interferometer modulates each source wavelength, stray light can be considered negligible. There is no direct equivalent of the stray light found in dispersive spectrometers. Moreover, resolution, which is defined in terms of resolving power or as a delta wavenumber, is constant at all wavenumbers in the spectral range defined.

The fact that the **ZOOM Spectra** has no moving parts and that the core of the instrument is a very small fully-integrated component guarantees highly robust wavelength calibration, which can last for a significant period of time and withstand many temperature fluctuations and frequent transportation. This offers a clear advantage over a standard Fourier Transform Spectrometer, whose mechanical scanning system is always a very limiting factor when it comes to calibration stability, as is the case in any complex dispersive spectrometer that features mechanical adjustments. And let us not forget how tiresome it is to conduct daily early-morning maintenance on a standard ultra-high resolution spectrometer!

SWIFTS™ TECHNOLOGY allows identical hardware to be used for a very broad spectral range of several hundred nanometers. And there are no discontinuities in the spectrum when performing simultaneous measurement, because no grating or filter changes are required.

What are the advantages compared to a wavelength meter?

- > Although the **ZOOM Spectra** can't offer exactly the same level of absolute accuracy as a high-end wavelength meter, it holds many advantages in cases where the use of a wavelength meter would normally be considered first. The essential point is that many tunable laser sources frequently deliver hopping modes and, in some cases, competing modes. These hopping modes are often unstable over a range of operating conditions and, within this range, the laser can switch from one mode to another very quickly. A wavelength meter has poor temporal resolution and will measure the average or give another wrong value of both modes whereas the **ZOOM Spectra** will perfectly distinguish the two. In the case of competing modes (two modes at the same time), the wavelength meter will also give only one wavelength value, i.e., the average of the two modes or another wrong value.

How the ZOOM Spectra works

More information is available in the **ZOOM Spectra**'s user manual.

If you have any other questions, please feel free to contact our experts at info@resolutionspectra.com

Wavelength-scale stationary-wave integrated Fourier transform spectrometry

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Abstract:

Spectrometry is a general physical analysis approach to investigate light-matter interaction. However, the complex designs of existing spectrometers hinder them from simplification and miniaturisation which are vital for current intensive research in micro- and nanotechnology. Stationary-wave integrated Fourier transform spectrometry (SWIFTS) - an approach based on direct intensity detection of standing wave issued by either reflection (as the principle of colour photography by G. Lippmann) or counterpropagative interference phenomenon - is deemed able to overcome this drawback. Here, we present a SWIFTS based spectrometer relying on an original optical near-field detection method in which optical nanoprobe is used to directly sample the evanescent standing wave in the waveguide. Combined with integrated optics, we report an elegant way of reducing the volume of spectrometer to a few hundreds of cubic wavelengths. This is the first attempt of SWIFTS in achieving very small integrated 1D spectrometer suitable for applications where micro-spectrometers are essential.

In 1891, at the "Académie des Sciences" in Paris, Gabriel Lippmann¹ presented a beautiful colour photograph of the sun's spectrum obtained with his new photographic plate. Later, in 1894², he published an article on how his plate was able to record colour information in the depth of photographic grainless gelatine and how the same plate after processing (development) could restore the original colour image merely through light reflection. He was thus the inventor of true interferential colour photography and received the Nobel Prize in 1908 for this breakthrough. Unfortunately, this principle was too complex to use. The method was abandoned a few years after its creation despite the considerable investment of Lumière brothers. At that time, one aspect of the

Lippmann concept that was merely ignored relates to spectroscopic applications. Within the context of micro nanotechnology and miniaturisation of spectroscopic equipments that nowadays are the subjects of intensive research^{3,4,5,6}, it becomes interesting to revisit the Lippmann concept. Actually early in 1933, Ives⁷ proposed to use a photo electric device to probe stationary waves to make spectrometric measurements. More recently, in 1995, P. Connes⁸ proposed to use arising new technology of detectors to make 3D Lippmann's based spectrometry. Following this idea, a first realisation of a very compact spectrometer based on Micro-Opto-Mechanical System (MOEMS) has been reported by Knipp et al.⁹ in 2005 but with a very limited spectral resolution. Based on the same concept, but taking advantage of photonics and near-field optics, we propose a new kind of Stationary Waves Integrated Fourier Transform Spectrometer (SWIFTS), in which direct sampling of evanescent standing waves is achieved using a collection of optical nanoprobes. The principle of SWIFTS is shown in Figure 1. Two configurations are proposed in which a direct near-field detection of confined standing waves is performed: the standing waves are issued either from a guided mode reflection as in G. Lippmann's principle of colour photography (figure 1a) or from two counterpropagative modes interference (figure 1b).

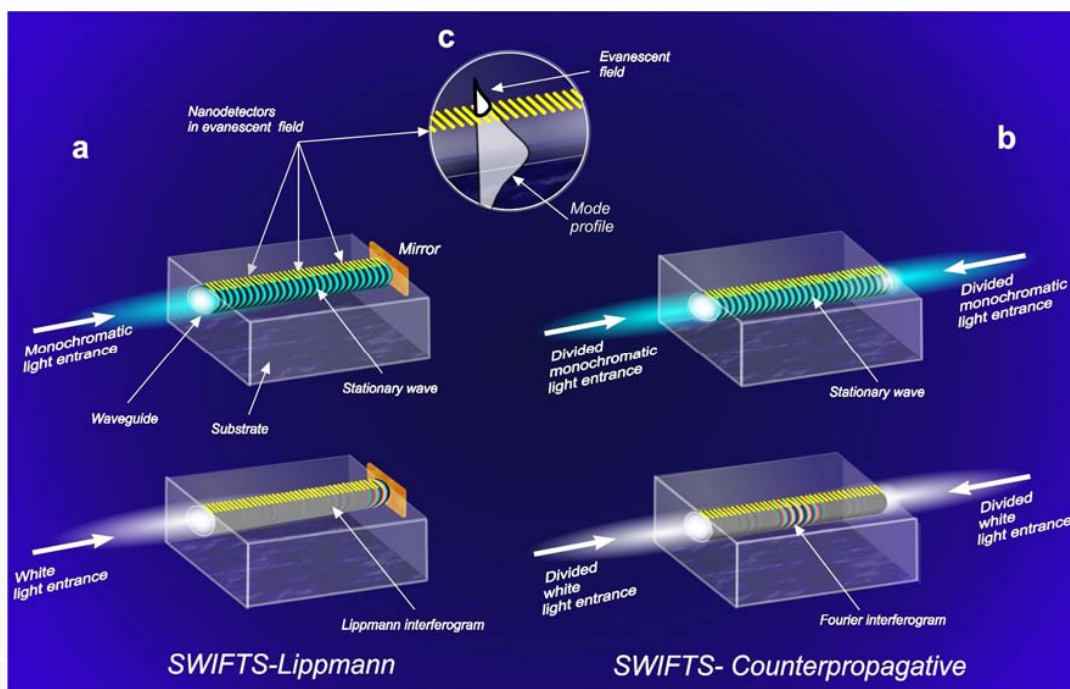


Figure 1 : Stationary Wave Integrated Fourier Transform Spectrometry. **a**, In the Lippmann onfiguration, the forward propagating wave coupled in the waveguide is reflected on the mirror, leading to a stationary wave. If light is polychromatic, the sum of the stationary waves forms a Lippmann interferogram. **b**, For the counterpropagative configuration, the light is divided upstream of the spectrometer. If the OPD between the two beams is null, the white fringe of the Fourier interferogram will be located at the waveguide centre. It is sensitive to the phase shift. **c**, Schematic of the near-field detection of the guided mode using a collection of nanodetectors.

In the first configuration, (figure 1a), light is coupled into a single mode waveguide terminated with a mirror. When reflected onto the mirror, waves become stationary. Miniature localized detectors are placed in the evanescent field (figure 1c) of the waveguide mode in order to extract as discussed further only a small fraction of the guided energy. This peripheral detection approach allows proper

sampling of the standing wave using relatively small size detectors in comparison with the quarter wavelength of the guided light. The interferogram resulting from white light illumination (figure 1a) bears Lippmann's name. Unlike a classical Fourier interferogram, Lippmann's interferogram starts at the surface of the mirror with a black null optical path difference fringe such that only one side of the fringe packet is detected. In this way the whole energy is recovered using a minimum number of detectors. This principle thus acts like a spectrometer with simultaneous recorded Fourier transforms, i.e. no moveable part is required to record the information needed to restore the spectrum.

The second SWIFTS configuration (figure 1b) is based on the same near-field detection idea but instead of using a mirror, the light is injected from both sides of the waveguide. A similar configuration has been proposed by Labeyrie¹⁰ for a data storage system which is an extension of holography^{11,12} or of a Sagnac interferometer¹³. In this configuration, the resulting interferogram is a typical symmetric Fourier interferogram (Fig. 1b) which, in contrast with the mirror configuration, is sensitive to the optical path difference. This type of spectrometer could therefore also be used in metrology.

RESULTS

SWIFTS performs analysis

Before addressing fabrication details and issues, we would like first to discuss on the typical characteristics that one would expect from spectrometers based on the SWIFTS concept. These typical characteristics include spectral resolution, efficiency and bandwidth. As in classical Fourier spectrometry, the spectral resolution achieved by SWIFTS is given by the length of the detected

interferogram: $R = \frac{\lambda}{\Delta\lambda} = \frac{2nL}{\lambda}$ where n is the effective refraction index of the waveguide, λ is the

wavelength, $\Delta\lambda$ is the resolved wavelength by the spectrometer and L is the waveguide length probed by the local detectors. In a single mode waveguide, the spectral resolution is only limited by the optical length (nL). Hence, SWIFTS spectrometer has no intrinsic limitation in resolution. For example, a SWIFTS spectrometer based on an optical waveguide including detectors placed over a length of 1cm (10^7 nm), would allow for a spectral resolution of about $R=40.000$ (15 pm) at a 600nm wavelength.

P. Connes⁸ has already note that an ideal Lippmann plate's efficiency can exceed 63%. Here, we theoretically and numerically demonstrate that an optimal efficiency of 74% can be obtained with SWIFTS assuming that each detector has ideal quantum efficiency and extracts exactly the same amount of energy $\eta_{loc} = 1/N$, where N is the total number of detectors (see § SWIFTS's internal efficiency in supplementary information).

Finally, the recoverable spectral range is ruled by two parameters: the sampling interval (i.e. the physical distance between two consecutive detectors) and the spectral range where the waveguide remains single mode. With a sampling interval satisfying the Nyquist's criterion, the recoverable spectral range is typically 400-500 nm for asymmetric waveguides at 1550nm, even more for symmetric waveguides and photonic crystal waveguides.

Design and construction

It is clear that to be fully efficient SWIFTS depends on the development of nanodetectors, which are not readily available as yet. For a very first demonstration, an intermediate solution based on light scattering was developed. The idea was to use nanometric scattering centres (see §Nearfield probe efficiency in supplementary information) deposited on the waveguide surface to extract the stationary field from the waveguide and thus make far field detection possible, using 2D planar detectors. Since we cannot use a detector array with a pitch equal to the quarter of the wavelength over a wide spectral domain, the Shannon's sampling criterion cannot be satisfied. However, if the spectral range is relatively small, the restoration of the spectrum still remains possible. This is known in Fourier spectrometry as the undersampling technique. For this first demonstration, the counterpropagative structure has been chosen (Fig. 1(b)). In addition to be sensitive to the optical path difference, this configuration avoids the technical problem of having a detector placed very close to the mirror.

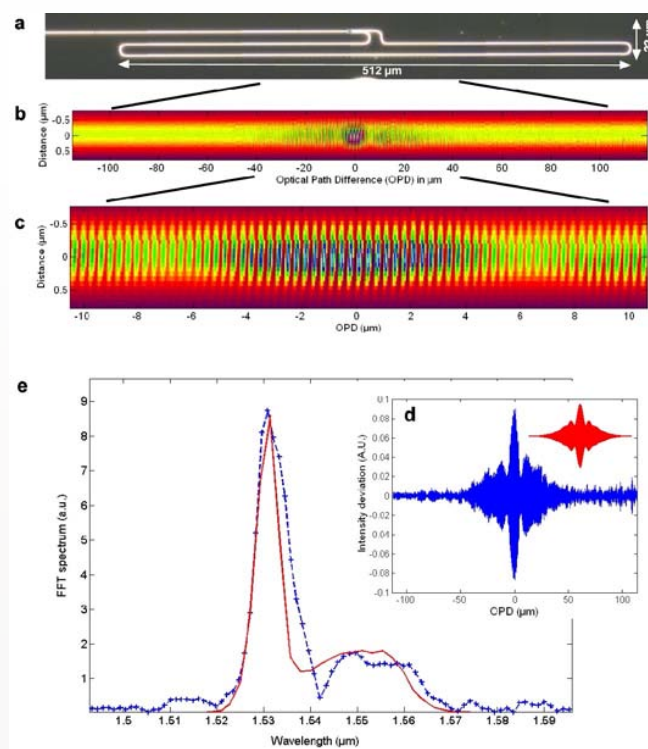


Figure 2 s-SNOM observation of an interferogram in a waveguiding structure. **a**, Top optical view of the interferometric component. The light of the ASE source is introduced into the guide and divided into two parts by an MMI, and propagates in opposite directions. The central fringe of the interferogram is equidistant from the MMI outputs. **b**, s-SNOM intensity image of the interferogram inside the component. **c**, 20 Å 1.5 mm² enlarged image of the image in **b**, where the central fringes appear as fine vertical features. **d**, Measured (blue) and theoretical (red) interferogram profiles. **e**, Reconstructed spectrum in blue is compared to the manufacturer's ASE spectrum

In the following section, in order to validate the SWIFTS concept we will first focus on the probing of the interferogram inside a waveguide by means of scattering scanning near field optical microscopy. Secondly, the possibility of using nanometric scale dots to image the interferogram

will be addressed and demonstrated. Hence we will show how a chain of nanowires can give a snapshot of the interferogram and thus allow recovery of the spectrum of an optical source.

Probing the interferogram inside the waveguide

The counterpropagative structure shown in figure 1(b) was fabricated using CMOS photonics technology. The silicon on insulator (SOI) substrate (200 mm wafer manufactured by SOITEC) used in this study is composed of a monocrystalline silicon layer with a typical thickness of 200 nm on top of a 1 μm thick buried oxide layer on a silicon substrate. After a silica hard mask deposition, the structure pattern is defined by means of a 193 nm deep UV lithography followed by hard mask etching and photoresist stripping. The pattern is transferred to the silicon layer by means of an HBr dry etching process. The entire waveguiding structure is then covered by a 700 nm thick cap layer of silica deposited by plasma-enhanced chemical vapour deposition. A chemical-mechanical polishing process is used to etch the capping layer until the planar structure has a uniform thickness of 100 nm.

An optical view of the full-size component, taken at the end of the process, is shown in figure 2(a). It mainly consists of a loop. The incoming light is introduced from the left side of the component into a straight single mode waveguide using a lensed fibre. To obtain single mode waveguides along a 1.5 to 1.6 μm wavelength range, a waveguide width of 500 nm has been defined on the mask. A multimode interference splitter (MMI) is used to equally couple the light into the loop. The central fringe (also called white fringe) of the interferogram is found where the Optical Path Difference (OPD) is cancelled, i.e. into the loop waveguide at an equal distance from the MMI outputs.

In a preliminary study, the device was characterized using a scattering-type scanning near field optical microscope¹⁴ (s-SNOM) which allows probing of the optical near-field of waveguides with nanometric resolution. A commercial Erbium-Amplified Spontaneous Emission (ASE) light source was used to couple the light into the waveguide. The broadband spectrum of this source in the telecom C-band centred around 1.55 μm was sufficient to demonstrate the stationary phenomena which forms into the loop.

The optical image shown in Figure 2b was obtained using a numerical stitch of nine s-SNOM individual 50x50 μm^2 scans in order to get a 50x220 μm^2 total scanned window centred on the white fringe position. As expected, the stationary nature of the guided field is revealed in the image by vertical lines (cf. figure 2c). Furthermore, the zero OPD can be localized where the standing wave visibility is maximal. The interferogram profile extracted from the s-SNOM image is shown in figure 2(e). Both measured (blue) and theoretical (red) stationary field intensity profiles are plotted in arbitrary units of intensity deviation for a better assessment. Since the counterpropagative device acts as a Fourier transform spectrometer, the incoming light spectrum is recovered by computing the Discrete Fourier Transform of the stationary field profile. The result is shown in figure 2(d). The spectrum, i.e. the Fourier Transform of the interferogram is compared with the spectrum of the reference source (ASE) obtained with an optical spectrum analyser. The spectra are very similar. Some slight differences are attributed to stitching uncertainties in the individual s-SNOM scans. It is worth noting that only the total length of the scan limits the spectral resolution of the experiment. Presently, with a scan length of $L=2 \times 110 \mu\text{m}$ around the central fringe, one obtains a spectral

$$\text{resolution } R = \frac{\lambda}{\Delta\lambda} = \frac{2nL}{2\lambda} = 323 \text{ leading to } \Delta\lambda \text{ of } 5\text{nm}.$$

Towards the nanostructured device

Although SNOM tips are ideal probes to sample the stationary field with nanometric resolution¹⁵, SNOM is not compatible with the idea of compact integrated and monolithic optical devices. Therefore, in order to provide a parallel and motionless detection of the stationary field, we proposed the use of distributed nanometric light scattering defects embedded in the waveguide near-field. For that purpose, a comb of 79 gold nanowires, made by e-beam lithography and lift-off process, was deposited along the waveguide. Each nanowire oriented perpendicular to the waveguide has the following properties: first of all, it is sufficiently long ($4\mu\text{m}$) to interact with the total transversal field. Secondly, it is narrow enough ($0.05\mu\text{m}$) to be considered as a point source scattering the light of the stationary field at a precise position. Finally, it is thin ($0.05\mu\text{m}$) enough to keep the volume small and thus only a small part of the field is scattered without disturbing the interferogram.

As shown by the AFM topography image (figure 3(a) and 3(b)), the crossing wires are arranged periodically with a pitch of $2.7\mu\text{m}$. Since the wires follow the initial rib Si waveguide topography, the wires look like a comb of equidistant pillars along the waveguide. Figure 3(c) is a far field image of the ASE stationary field sampled with the nanostructured waveguide. This image is the result of the scattering of 29 consecutive gold nanowires centred on the white fringe. Each light scattering defect is well resolved. Clearly, one can see that the detected signal is not perfectly symmetric from the zero OPD point. This is most probably due to a slight inconsequent misalignment between the central metallic wire and the white fringe maximum.

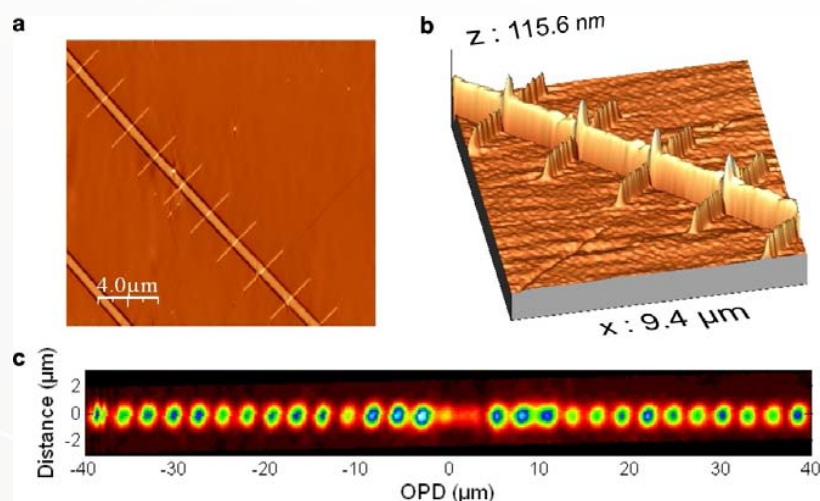


Figure 3: nanowires structures: **a)** AFM topography image of the nanostructured waveguide surface showing nine $4\mu\text{m} \times 50\text{nm}$ lithographic gold stripes crossing the silicon waveguide. **b)** Topographical 3D view **c)** Far field image of the ASE stationary field sampled by the 29 gold nanowires. The image is centred around the undersampled central fringe area

For calibration matters, the device was then characterized in the far field with a microscope objective, an InGaAs infrared camera and a single mode CW tuneable Er laser. Figure 4(a) shows a snapshot of the scattered light at a wavelength of 1510 nm . By computing the Fourier Transform of the longitudinal profile of the sampled interferogram, one obtains the laser light spectrum (Fig4(b)). This experiment gives an accurate calibration of the relation between the absolute wavelength and

the measured spatial frequency. The process can be reiterated for the whole laser tuning range to obtain the curve in figure 4(c).

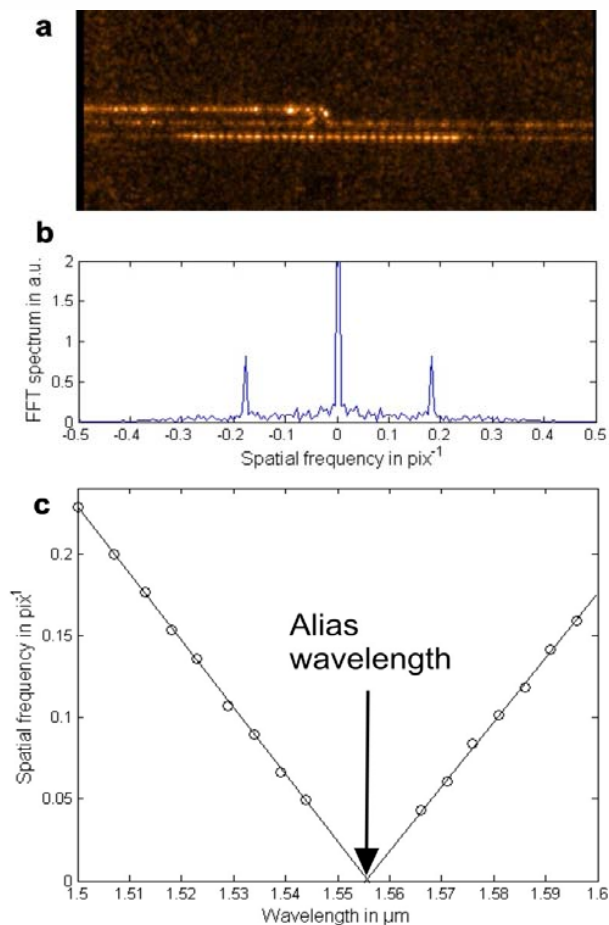


Figure 4: monochromatic illumination: **a)** image of the central part acquired with an infrared microscope. Tuneable laser fringes are seen as a chain of dots. **b)** Fourier transform of the recorded profile along the waveguide section on which gold nanowires have been deposited. The spatial frequency can be precisely deduced from the symmetric peaks. **c)** Plot of the spatial frequency versus the wavelength showing the aliasing effect. An alias wavelength at 1.55 μm corresponds to a 2.7 μm nanowire spacing with an effective refractive index of 2.301.

The wavelength limits of the recoverable spectrum can be found applying the band pass sampling theory¹⁶. For a stationary wave with spatial frequencies $f = \frac{2n_{\text{eff}}(\lambda)}{\lambda}$ lying in the range $[f_{\text{min}}, f_{\text{max}}]$, and a sampling frequency m times lower (m is an integer) than the Nyquist's frequency $f_N = 2f_{\text{max}}$, d_z is the distance between two nanowires. We obtain:

$$\begin{cases} \lambda_{\min} = \frac{4n_{\text{eff}}(\lambda_{\min})}{f_N} = \frac{4n_{\text{eff}}(\lambda_{\min}) \cdot dz}{m} \\ \lambda_{\max} = \frac{n_{\text{eff}}(\lambda_{\max})}{n_{\text{eff}}(\lambda_{\min})} \frac{m}{(m-1)} \lambda_{\min} \end{cases}$$

As a consequence, any component of a sampled signal with a wavelength outside these limits, often referred to as the aliasing window, is subject to folding. This is clearly observed in figure 4(c): wavelengths above the value $1.555 \mu\text{m}$ are folded into the aliasing window. Furthermore, the measurement of the alias wavelength leads to the value of the under sampling factor $m=17$. The sampling factor being a constant, this means that by measuring the position of the peak for each wavelength in the tuneable laser range, the dispersion relation of the waveguide $n_{\text{eff}}(\lambda)$ can be retrieved. As for polychromatic measurements a dispersion correction is needed, this procedure enables us to calibrate the SWIFTS spectrometer. The spectrum shown in Figure (4c) has been corrected for the effective refractive index dispersion.

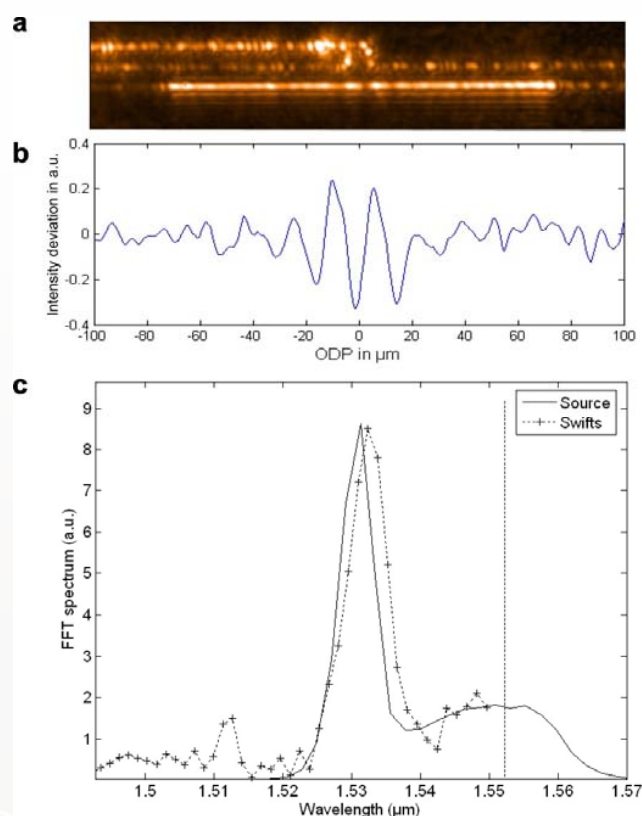


Figure 5: polychromatic illumination: **a)** microscopic image recorded with an infrared camera, the periodic dashed lines in fig. 4 are replaced by the Erbium fluorescence under-sampled interferogram. **b)** Extracted interferogram extending $200 \mu\text{m}$ around the central fringe. **c)** Reconstructed (cross) spectrum, limited to long wavelengths by the aliasing windows, compared to the reference spectrum (solid line) recorded with a spectrum analyser.

Finally, the SWIFTS spectrometer was tested with an Er-ASE broadband source. The results are depicted in figure 5. The NIR camera snapshot is shown in figure 5(a). The stationary wave profile sampled by the gold wires is shown in figure 5(b). The spectrum recovered after calibration is plotted as a dotted line in figure 5(c) in contrast with the reference spectrum (solid line) obtained

from a spectrum analyser. The Erbium fluorescence spectrum is well recovered up to the alias wavelength. This experimental result is very promising, especially if one takes into account the defects (merely surface scattering) inherent to a first realisation. However, a small unexpected bump is visible on the left side of the spectrum. It is probably due to a mismatch between the interferogram sampling interval and the CCD pitch and could be removed by an appropriate choice of the optical system magnification. Further work is required to fully understand this effect.

DISCUSSION

The Lippmann concept of spectroscopy based on the Fourier Transform was never efficiently exploited until now. In this paper, a near field method to probe the interferogram within a waveguide has been proposed and demonstrated. The concept has been first validated using a scanning near field optical microscope. A first step towards fully integrated spectrometer has been made by local deposition of gold nanowires on the waveguide surface. Gold nanowires were $2.7 \mu\text{m}$ spaced in order to allow for far field probing using a simple CCD. With this structure it is clearly demonstrated that small gold wires are able to both scatter the light and sample the interferogram, allowing its detection.

The nanostructured waveguide we have developed can be seen as precursor of a new generation of spectrometers. This 1mm sized device has a spectral resolution of 4nm over a working spectral range of 96nm centred on 1500nm. At this stage a comparison with the State-of-the-Art integrated optical microspectrometers is untimely. However it is important to underline that the SWIFTS concept opens the route to very compact spectrometers with noteworthy features: high resolution, instantaneous measurement and no requirement for any moveable or tuneable parts. This has to be compared with classical Fourier Transform Spectrometry (FTS)^{17,18} for which either the interferogram is sequentially recorded or statically projected onto a two dimensional detector array.

Further developments lie in using existing detectors arrays directly placed in the vicinity of the scattering centres. Fully integrated SWIFTS spectrometers will become manufacturable but with a limited efficiency. In future, the ultimate development will consist in replacing the gold nanowires by specially-designed detectors set every quarter of the standing wavelength. This will also enlarge the spectral bandwidth of the fully integrated spectrometer within the limitation of the single mode operation of the waveguides. It is worth mentioning here that a few of these nanoscale detectors already exist such as Superconducting Single Photon Detector (SSPD)¹⁹ and carbon or silicon nanotubes.

Finally, it has to be stressed that while making spectroscopic instruments more robust and cheaper through the use of integrated technologies, SWIFTS is a general concept that paves the way for a number of applications and especially in optics where micro-spectrometers are essential. These applications would be space-borne spectrometry, metrology, endoscopy, gas and chemical sensors, colour photography and parallel spectral imaging.

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Competing financial interestes

The authors declare that they have no competing financial interests

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