Wideband RF spectral analyzer based on spectral-spatial holography in Tm$^{3+}$:YAG achieved with a highly stabilized frequency chirped laser

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Abstract

We demonstrate a 10 GHz spectrum analyzer with MHz resolution and a 30 dB dynamic range using the spectral hole burning (SHB) Tm$^{3+}$:YAG crystal working at 793 nm. Thanks to the fast and linear chirping capabilities of the laser used, it has a potential 100% probability of interception and a response time in the ms range. The system is compared to a previously demonstrated SHB spectral analyzer. We also investigate theoretically and experimentally the requirements for the frequency chirped laser sources spectral purity and their influences on the precision of our experiment.

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1. Introduction

Radar signal processing or (sub) millimeter astronomy needs very sensitive processing techniques to analyze signals spanning GHz of bandwidth with 100% probability of interception. Because optoelectronic solutions present broad bandwidth capabilities more naturally than electronics, they are under active development for Radio Frequency (RF) signals spectral analysis. At the moment the most widely used optoelectronic spectrometer is the acousto-optic spectrometer (AOS) [1]. However, the bandwidth of this device is currently limited to 2 GHz. Furthermore, these spectrometers must be designed with fixed bandwidth and resolution. Consequently, they are not flexible regarding different kinds of observations. In order to cope with the increasing bandwidth demand, one needs an alternative technology with great potential for future laboratory experiments.

The emerging spectral hole burning (SHB) technologies have the potential to treat large bandwidth signals. In particular, the inhomogeneous broadened absorption bands of rare-earth-doped crystals can have bandwidths that exceed tens of GHz together with a spectral resolution well below 100 kHz at cryogenic temperature [2]. A spectral analyzer exploiting the wide bandwidth potentialities of SHB has been first demonstrated by Lavielle et al. [3]. Quite similarly to an AOS, this setup spatially separates different RF spectral components. This architecture has demonstrated 3.3 GHz bandwidth, sub-MHz resolution and zooming capability. However, it suffers from two main drawbacks: (i) its spatial demultiplexing principle makes the channel capacity difficult to increase; (ii) its optical scheme is rather complicated to implement. Recently a more direct and completely different approach called “photographic scheme” based on Tm$^{3+}$:YAG crystal SHB spectrum analyzer has been developed [4,5]. It consists in engraving the optically carried RF signals to be analyzed in the populations of the rare-earth-ions by SHB phenomenon and to read the spectra with a chirped laser. Both systems have demonstrated a 10-GHz bandwidth with 10 000 channels capacity and a resolution in the MHz range [4,5]. The weakness of the “photographic scheme” spectral analyzer is its dynamic range of 20 dB which is limited by the presence of a large background signal. We consider we are within the dynamic range as long as the signal amplitude varies linearly with the engraving RF power. In order to improve this figure while

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keeping a 10 GHz bandwidth and a MHz resolution, several paths can be explored. For example, several beam configurations and an adapted detection scheme can be implemented.

Furthermore, to preserve the “photographic scheme” analyzer precision and resolution of 1 MHz, the reading laser must achieve broad and fast frequency scans (typically 10 GHz in 1 ms) with high linearity and reproducibility. This means that the frequency deviation from a perfectly linear chirp has to be much lower than 1 MHz. Thus the development of a stabilization system to precisely control and stabilize the chirping laser along the lines drawn in Ref. [6] is necessary for the success of our new generation of SHB spectral analyzers.

Section 2 of the present paper describes the “photographic scheme” spectral analyzer principle of operation. A description of the different configurations, namely collinear and holographic, together with the associated engraving and reading beam geometries, is presented. In Section 3, we describe the experimental characteristics of the holographic configuration in comparison to the collinear one. In Section 4, we describe our servo-loop control of the reading laser frequency and how the stabilization system improves our system resolution.

2. SHB spectral analyzer

2.1. Principles of operation

As already mentioned, the spectrum photography architecture is the simplest of the SHB spectral analyzer configurations. Its principle of operation can be understood from the scheme of Fig. 1. The key element of the setup is the Tm$^{3+}$:YAG crystal (see Fig. 1(a)). Indeed, the bandwidth, resolution and spectral photograph lifetime are imposed by the choice of the SHB material. The use of the absorption transition of Tm$^{3+}$ at 793 nm exhibits the required characteristics: a 25 GHz inhomogeneous linewidth $\Gamma_{inh}$ and a homogeneous linewidth $\Gamma_h$ of about 150 kHz. Thus, $\Gamma_{inh}$ and $\Gamma_h$, respectively, play the role of bandwidth and resolution of the spectral analyzer. By using a Mach–Zehnder modulator, the RF signal of interest (see Fig. 1(b)) is transferred on an optical carrier provided by a laser operating at fixed frequency centered on the SHB material absorption profile. Using this modulation scheme, the RF power spectrum is thus directly transformed into an optical power spectrum. The modulated optical beam lights the SHB crystal and excites the ions that are resonant with the different RF spectral components. Consequently, the optically carried RF spectrum is recorded in the material absorption bandwidth, as shown in Fig. 1(c). The lifetime of this spectral photograph depends on the population relaxation time of the system. During this lifetime, the spectrum is read out with a laser whose frequency is scanned over the whole absorption profile, as shown in Fig. 1(d). The frequency chirped reading laser is an external cavity diode laser (ECDL) closed by a grating in Littrow configuration. It contains a prismatic LiTaO$_3$ electro-optic crystal (EOC) which turns the laser in an optical voltage controlled oscillator characterized by a scale factor $K = 12.5$ MHz/V. Its frequency is chirped by applying a voltage ramp on the EOC [7]. Thus, by simply measuring the SHB crystal transmission versus time, one recovers the RF spectrum (see Fig. 1(e)). From Fig. 1(a), one clearly sees that the use of two different lasers for engraving and probing is sufficient to ensure a 100% probability of interception of incoming RF signals. Depending on the relative orientations of the engraving and reading beams of Fig. 1(a), two main architectures can be distinguished.

2.2. Collinear and holographic architecture

The principles of the collinear and holographic spectrum analyzers are summarized in Fig. 2. The collinear configuration is the one implemented in Refs. [4,5]. As
schematized in Fig. 2(a, b), the engraving beam $E_W$ and the probing beam $E_P$ are collinear. This latter field probes the susceptibility of the material which has been modified by $E_W$. This susceptibility gives rise to a macroscopic polarization that radiates the field $E_{RF}$. Owing to causality, the atomic response can be decomposed in a real and an imaginary part: $E_{RF} = E_R + iE_I$, where $E_R$ and $E_I$ are, respectively, the absorption and dispersion components of the atomic response. In all this discussion, we neglect the linear dispersion associated with interrogating narrow holes with fast chirps [8]. Since $E_{RF}$ and $E_P$ are collinear, the detected intensity is given by

$$I = E_P^2 + 2E_P E_R + E_R^2 + E_I^2 \approx E_P^2 + 2E_P E_R,$$  

where $E_P$ represents the transmitted probe beam at the crystal output. By considering our SHB crystal as a thin material, we can assume that the quadratic terms of the atomic response are weak compared to $E_P^2$. This equation perfectly illustrates the pros and cons of the collinear architecture. Indeed, it shows that the term $E_I$ can be neglected thanks to the homodyning with the transmitted probe field amplitude $E_P$. This leads to a good fidelity in the reproduction of the engraved spectra and a resolution limited by $I_R$. The drawback of this approach is that the term $E_I^2$ is very large and leads to a strong noise which severely limits the signal to noise ratio of the analyzer.

To circumvent this problem, we choose to shine the sample with no longer one but two engraving beams, as seen in Fig. 2(c). The two engraving beams both carry the same RF signal and are separated by a small angle in the SHB crystal. Consequently, they engrave a spatial grating only in atoms which are resonant with their spectral components. To read this family of gratings, the chirped probe beam is then incident along the direction of one of the engraving beams, as seen in Fig. 2(d). This probe beam will then be diffracted by the gratings engraved in the absorption bandwidth only when it corresponds to an engraved frequency. As a result, the atomic response $E_{RF} = E_R + iE_I$ can now be detected on a dark background. The detected intensity is given by $I = E_R^2 + E_I^2$. As expected, the holographic configuration allows a background free measurement and the noise associated with the probe laser disappears. However, we now face two new problems. First, the detected power is proportional to the square of the RF power, leading to a decrease of the sensitivity of the analyzer. Second, the system is now also sensitive to the imaginary part of the atomic response, which strongly degrades the spectral resolution of the system. To get rid of the dispersive part of the atomic response, one has to perform a heterodyne detection of the diffracted beam. To this aim, a fraction of the probe beam is frequency shifted by an acousto-optic modulator operating at frequency $F$ and mixed with the diffracted field before it reaches the detector. The detected intensity is then given by

$$I = E_{LO}^2 + E_R^2 + E_I^2 + 2E_{LO}E_R \cos(2\pi Ft) - 2E_{LO}E_I \sin(2\pi Ft),$$  

where $E_{LO}$ is the local oscillator field amplitude. According to Eq. (2), one can see that (i) the signal intensity is again proportional to the RF signal intensity; (ii) the detection does no longer occur on a dark background, due to the presence of the local oscillator intensity. In order to isolate the term of interest $E_{LO}E_R$, we multiply Eq. (2) by a cosine function at frequency $F$ with the correct phase reference. The phase term must be fitted by a digital algorithm during the post processing demodulation. The demodulation process leads to

$$E_R E_{LO} [1 + \cos(4\pi Ft)] + E_{LO}^2 \cos(2\pi Ft) - E_I E_{LO} \sin(4\pi Ft).$$

The resulting signal is composed of a continuous term $E_{LO}E_R$ and two components oscillating at frequencies $F$ and $2F$. Thus by applying a digital filter with a cutoff frequency of 3 MHz, one can isolate the DC term $E_{LO}E_R$ and find back the resolution of the collinear configuration. Furthermore, the pertinent component of the relative intensity noise of the laser has been shifted to the heterodyne frequency and a shot noise limited measurement is easier to reach. Optimization of the signal to noise ratio of the analyzer, i.e., of its dynamic range, hence consists in increasing the local oscillator power to increase the signal of Eq. (3), till the total detected power reaches the saturation limit of the detector for the maximum value of the power diffracted by the ions. In the next part, we experimentally characterize the holographic configuration and compare it to the collinear one [4,5].

3. Experimental demonstration of the holographic architecture

The holographic architecture with heterodyne detection has been experimentally investigated. For this demonstration we engrave and read the RF spectra of interest using the same ECDL [7]. During the engraving step, we mimic the optically carried signals by applying different voltages on the EOC of the ECDL. The evolution of the engraving laser frequency during the experiment follows the voltage applied to the EOC. The amplitude and the duration of engravings at the different frequencies are controlled by acousto-optic modulators. The waists of the beams in the crystal are equal to 500 $\mu$m. The angle set between the writing beams is around 3.7 mrad.

3.1. Holographic architecture bandwidth

In this part, we check that the holographic system has the same bandwidth characteristics as the collinear architecture [4,5]. An example of 10-GHz bandwidth spectral analysis is
reproduced in Fig. 3. The engraved spectrum consists in a series of 16 spikes each lasting 200 µs with the laser tuned over the 15 different frequencies. The reading is performed with a 10 GHz bandwidth scanned in 2 ms. During the engraving and reading phases, the optical power is about 1 mW. One can notice an amplitude fluctuation of the 10 GHz spectrum. These oscillations are due to a modulation of the reading laser intensity when this one is chirping. These fluctuations are deterministic and perfectly known [6]. Both architectures thus present the same characteristics in terms of bandwidth and spectral resolution. In the following subsection, we investigate whether the holographic configuration permits to improve the dynamic range as compared with the previous demonstration.

3.2. Dynamic range

This dynamic range can be extracted from the experimental results reproduced in Fig. 4. This figure represents the evolution of single peak readout amplitude versus engraving optical energy. The experimental points have been obtained by varying the engraving beams power between 0 and 3 mW with a constant engraving duration of 700 µs. The engraved peak is read after a time delay equal to 1.2 ms with the probe laser (6 mW) scanning over 1.25 GHz in 2 ms. We heterodyne the diffracted field with a local oscillator (20 µW) shifted of 8 MHz with respect to the probe field. These measurements exhibit a saturation behavior that can be reproduced from the coupled-mode theory [9]. We are within the useful dynamic range for signal amplitudes between 0 and 45 mV. By comparing these signals with the typical noises reproduced in the inset of Fig. 4, one can deduce the dynamic range. The standard deviation of the noise is 40 µV on a 3 MHz bandwidth. We finally obtain a dynamic range of 31 dB (for a 3 MHz bandwidth). As predicted, because the holographic architecture is not sensitive to the low-frequency part of the intensity noise, its dynamic range is larger than in the collinear case. Indeed, for the same experimental parameters, the dynamic range of the collinear architecture is 20 dB (for a 3 MHz bandwidth). Thanks to the holographic architecture with heterodyne detection, we now have a signal-to-noise ratio limited by the shot noise. By working with detectors presenting higher saturation levels, one can further increase the dynamic range.

4. Servo-loop control of the chirped reading laser linearity and spectral purity

All the RF spectrum analyzers, presented in Section 1, require frequency agile lasers to cover tens of GHz in the ms timescale, with an intrinsic stability much better than the aimed resolution. With such broad scans and large chirp rates, high linearity is necessary to provide the spectrum analyzer resolution and absolute precision of 1 MHz. A complete measurement of the laser frequency noises during the frequency scan has been performed [6] by using an unbalanced interferometer. Moreover, this setup can be used to build a servo-loop control of the chirped laser frequency with a correction signal applied on the electro-optic crystal (EO) of the laser. To correct the frequency errors occurring during the chirp, we need to measure the laser frequency instantaneously. As already presented in Ref. [6], this can be performed by measuring the voltage ramps

Fig. 5. Experimental setup used to characterize the frequency noises occurring during the chirp.
two signals in quadratures at the output of an unbalanced Mach–Zehnder with a time delay $\tau_d = 30.7\) ns, as schematized in Fig. 5. When we chirp the probing laser, its instantaneous frequency can be expressed as $\nu(t) = \nu_0 + rt + \delta \nu(t)$, where $\nu_0$ is the average optical frequency, $r$ is the chirp rate and $\delta \nu(t)$ represents the frequency errors. The beat note phase detected at the interferometer output can be expressed as $2\pi f_b t + \phi_0 + C(t)$, where $f_b = rt_d$, $\phi_0$ is a constant phase term and $C(t) = 2\pi \tau_d \delta \nu(t)$. Thus, the phase can be unambiguously extracted provided we detect two signals in quadrature at the interferometer output. The desired phase difference of $\pi/2$ between the two signals is obtained by using an assembly of polarization components and two photodiodes as schematized in Fig. 5. Thus we simultaneously measure

$$I_c(t) = I_0 \cos(2\pi f_b t + \phi_0 + \Psi(t)),$$

$$I_s(t) = I_0 \sin(2\pi f_b t + \phi_0 + \Psi(t)),$$

where $I_0$ is the amplitude. To experimentally measure the phase term related to the frequency errors, we use a homemade digital processing unit device. It is composed of 8-bit converters and of a field programmable gate array (FPGA) with a sampling rate of 1 MHz. This system allows us to make simple operations with reference signals $\sin(2\pi f_b t + \phi_0)$ and $\cos(2\pi f_b t + \phi_0)$ to extract an error signal according to

$$\varepsilon(t) = I_c(t) \sin(2\pi f_b t + \phi_0) - I_s(t) \cos(2\pi f_b t + \phi_0)$$

$$= I_0 \sin(2\pi \tau_d \delta \nu(t)).$$

Eq. (5) shows that $\varepsilon(t)$ behaves as a sine wave as a function of the laser frequency error with a period given by $1/\tau_d$ (30 MHz in our case). If an active stabilization is done, the frequency errors will remain small and $\varepsilon(t) \approx I_0 2\pi \tau_d \delta \nu(t)$. Thus, $\varepsilon(t)$ becomes directly proportional to the laser frequency error and after filtering can be used as a correction voltage. A simple spectral study of $\varepsilon(t)$ leads to the power spectral density (PSD) of the laser frequency noise. As presented in Ref. [6], the spectral purity degradation of a chirped laser is mainly due to technical noises. In order to compare these noises with and without the stabilization, we resort to laser frequency noise PSD measurements when the frequency is scanned over 10 GHz in 4 ms. The spectra are presented in Fig. 6(a). When the loop is open (resp., close), the standard deviation associated to this noise in a 0.25–200 kHz integration band is about 250 kHz (resp., 17 kHz). The influence of the active stabilization process on a SHB experiment is presented in Fig. 6(b). The experiment consists in engraving a single spectral hole in the crystal absorption bandwidth and simply read it with our ECDL scanned over 10 GHz in 4 ms. When the altered absorption profile is read without

Fig. 6. Experimental and theoretical results obtained when the laser is chirped over 10 GHz in 4 ms (gray: open loop; black: closed loop). (a) and (c) Experimental and theoretical chirped laser frequency noise PSD. (b) and (d) Experimental and theoretical readout of a spectral hole.
(resp. with) stabilization of the frequency chirp, the spectral feature exhibits a linewidth of 3.25 MHz (resp., 1.5 MHz). This experiment shows that increasing the chirp spectral purity improves the spectral analyzer resolution. Because of the better chirp spectral purity, the readout gets the behavior predicted in Ref. [8]. Indeed, one can see the expected ringing in the detected signal. The spectral linewidth obtained when the loop is on is still larger than the absolute limit given by the crystal homogeneous linewidth because of the contribution of the engraving laser frequency jitter and the remaining noise of the chirped laser. Using the laser noise characteristics described by Fig. 6(a) and the model based on the propagation of chirped electric field in a spectrally shaped media [8], one can explain the SHB experiment improvement in terms of resolution by using a stabilized frequency chirped laser. In this model, we start by simulating the PSD of the frequency noise. In accordance with PSD data, we consider the non-stabilized laser follows a $1/f^2$ frequency law between DC and 200 kHz and exhibits white noise characteristics at higher frequencies. The servo-loop controlled laser presents a white noise frequency law between 0 and 1 MHz. To generate the time series exhibiting the desired DSPs, we use the algorithm proposed by Timmer et al. [10]. As a result, the numerically generated DSPs are presented in Fig. 6(c). The generated time series can be used as a temporal frequency noise to simulate the analysis of a Lorentzian spectral hole with FWHM $\Gamma_h$ [8]. The resulting spectral features readout with an unstabilized (or stabilized) chirped laser are presented in Fig. 6(d). These simulations are in rather good agreement with the experimental results. When the altered absorption profile is read without (resp. with) stabilization of the frequency chirp, the spectral feature exhibits a linewidth of 3.1 MHz (resp., 1.7 MHz). These computations demonstrate the importance of stabilizing the reading laser for spectral analysis applications.

5. Conclusion

We have reported a 10 GHz bandwidth photographic spectral analyzer with 10000 channels capacity and a resolution in the MHz range based on holography in Tm$^{3+}$:YAG. This spectrum analyzer has a potential 100% probability of interception and a fast response time. This analyzer presents a much larger dynamic range than the collinear one. A servo-control of the reading laser frequency allows us to control the frequency scan with a precision better than 1 MHz. The improvement of the spectrum analyzer resolution thanks to the stabilization process has been theoretically and experimentally demonstrated.

References