

# Spectral hole burning for wideband, high-resolution radio-frequency spectrum analysis

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We present experimental results for what is to our knowledge the first spectral-hole-burning based rf spectrum analyzer to cover 10 GHz of rf analysis bandwidth. The rf signal of interest is modulated onto an optical carrier, and the resultant optical sidebands are burned into the inhomogeneously broadened absorption band of a  $\text{Tm}^{3+}$ :YAG crystal. At the same time a second, frequency-swept laser reads out the absorption profile, which is a double-sideband replica of the rf spectrum, and thus the rf spectrum can be deduced after spectral calibration of the nonlinear readout chirp. This initial demonstration shows spectral analysis covering 10 GHz of bandwidth with >5500 spectral channels and provides 43 dB of dynamic range. © 2005 Optical Society of America

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Spectral-hole-burning (SHB) and spatial-spectral holography techniques have been used in photonic signal processing demonstrations for applications such as high-bandwidth signal correlation,<sup>1</sup> arbitrary waveform generation,<sup>2</sup> high-bandwidth rf imagers,<sup>3</sup> unity-probability-of-intercept rf spectrum analyzers,<sup>4-6</sup> and radar ranging systems.<sup>7</sup> Spectral hole burning is the process by which spectrally varying absorption features are formed in materials that contain inhomogeneously broadened absorbers (IBAs). If these spectral features also have spatial variation, they are typically referred to as spatial-spectral holograms. The narrow homogeneous lines of cryogenically cooled rare-earth ions doped into a crystal lattice are shifted throughout a wide inhomogeneous band by the variation of the ions' local environments. In 0.5% doped  $\text{Tm}^{3+}$ :YAG cooled to 4.8 K, the inhomogeneously broadened linewidth spans  $\Gamma_I = 25$  GHz, while the homogeneous absorption width is  $\Gamma_H \approx 100$  kHz.<sup>8</sup>  $\text{Tm}^{3+}$ :YAG is a two-level system with an intermediate bottleneck state, so any spectral features written into  $\text{Tm}^{3+}$ :YAG will persist for, and can be read out during, the bottleneck state's lifetime,  $T_B = 10$  ms.

Wideband spatial-spectral holographic signal processing based on photon echoes produces high-bandwidth correlations through spectral domain multiplication.<sup>1</sup> However, as this process produces output echoes with bandwidths commensurate with the input bandwidths, an input-output problem remains when these systems are used to process high-bandwidth signals. The more recent spatial-spectral coherent holographic integrating processor approach<sup>7</sup> circumvents the high-bandwidth output problem by recording high-bandwidth spectral features in the SHB medium and then leisurely reading them out with a slow, chirped optical source, detecting on a low-bandwidth, high-dynamic-range detector, digitizing, and performing postprocessing. The appeal of this approach is its ability to convert high-bandwidth

rf signals into a low-bandwidth processed output that is easy to detect with a corresponding high dynamic range. Whereas the bandwidths of these IBA materials can be as high as 200 GHz in inorganic crystals,<sup>9</sup> creating an optical signal that linearly sweeps over such bandwidths while it remains accurate to within the material's resolution (typically submegahertz) is nontrivial. Electronically generated chirps can be modulated onto a cw laser, or, alternatively, the laser can be optically chirped. The first approach requires that a precise, high-bandwidth rf chirp from an rf sweeper, a direct digital synthesizer, an arbitrary waveform generator, or a pulse-pattern generator modulate a stabilized cw laser via a high-bandwidth electro-optic modulator (EOM). These approaches place a great burden on the rf electronics because multioctave, phase-continuous, multigigahertz rf sweepers are in themselves difficult to obtain. In contrast, a chirping laser that sweeps through the inhomogeneous absorption band of the material can easily cover several tens or even hundreds of gigahertz to read out the spectrum engraved into the IBA. Unfortunately, most chirping laser systems inherently chirp nonlinearly over the bandwidths of interest. However, it is possible to correct the temporal distortion of the spectral scan after detection by extending a well-known spectroscopic technique, in which the nonlinearity of the chirp is measured by an etalon,<sup>10</sup> to substantially higher resolution by use of a long fiber as the etalon. We use a commercial external-cavity diode laser (ECDL) and modulate its frequency with a smooth sinusoid applied to the frequency tuning piezoelectric transducer of the ECDL. We then postprocess any deviations from the ideal chirp by reading out not only the spectral features in the SHB crystal but also a fiber etalon's periodic spectral response. This approach requires only minimal postprocessing to linearize the readout spectrum. We describe the experiment and then present results for a 10 GHz (5 GHz double-sideband) spectrum analysis

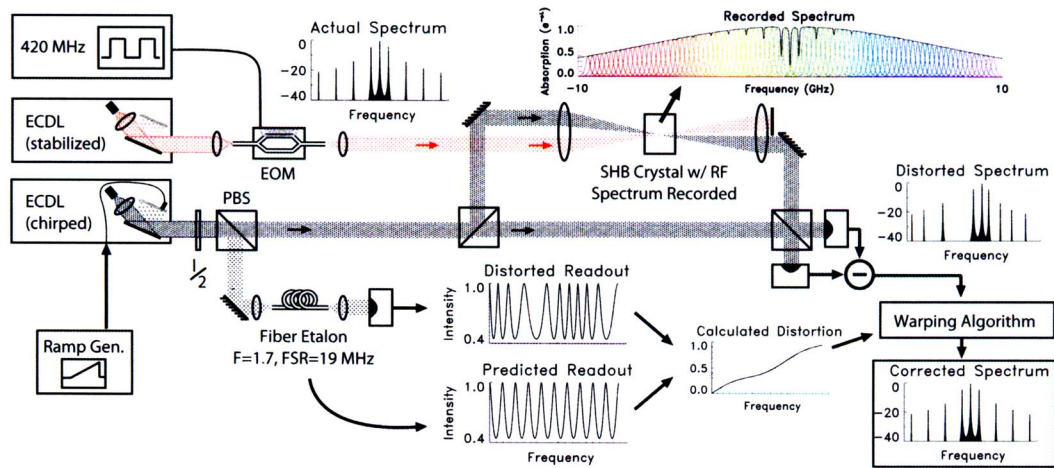


Fig. 1. (Color online) High-bandwidth SHB spectrum analysis experiment: An EOM modulates the output of a frequency-stabilized ECDL with a 420 MHz square wave. The resultant spectrum is engraved in the SHB and read out in  $<5$  ms with a frequency ramped ECDL. As the frequency ramp has standard deviations of  $\sim 20$  MHz, a spectral reference (fiber based etalon) is simultaneously interrogated, facilitating spectral correction in low-bandwidth postprocessing. FSR, free spectral range; PBS; polarizing beam splitter.

experiment that shows greater than 43 dB of dynamic range and frequency deviations from the original spectrum that are below the 1.8 MHz resolution of the experimental spectrum analyzer.

Illuminating the IBA with an electro-optically modulated stable laser will burn both spectral sidebands of the wideband rf signal into the absorption band of the crystal. This modulated absorption spectrum contains imprints of the rf spectrum and can be read out with a frequency-swept laser, thus facilitating wideband rf spectrum analysis.<sup>5,6</sup> Previous demonstrations of spectrum analysis were inherently limited to only a few gigahertz by the rf generators required for reading out the spectral grating; instead, our use of a calibrated, carrier-swept laser permits operation over 80 GHz.

The greatest advantages of using IBAs in rf spectrum analysis are the huge instantaneous time-bandwidth products (greater than  $10^4$ ; i.e. submegahertz resolution over more than 20 GHz), the fact that all spectral channels are accumulating their resonant signals in parallel, the ability to read out the spectral features of the SHB medium sequentially within lifetime  $T_1$ , and the rapid update of the rf spectral measurements. These properties are in contrast to those of scanning superheterodyne spectrum analyzers, which have a dwell time associated with each spectral channel and can thus miss the pulsed or frequency-hopping emitters that would be picked up by IBA-based spectrum analyzers.

The experimental setup is illustrated in Fig. 1. A null-point biased, 20 GHz amplitude EOM ( $V_\pi = 1.6$  V) is driven by a 420 MHz square wave ( $V_{pp} = 0.8$  V) and modulates the 793.4 nm optical carrier from a frequency-stabilized New Focus Velocity laser,<sup>11</sup> yielding the optical sidebands that we wish to record in the IBA. The rf sidebands are also characterized with an electronic spectrum analyzer for the comparison illustrated in Fig. 2. The optical power of this beam (at quadrature bias) is  $\sim 3$  mW and is fo-

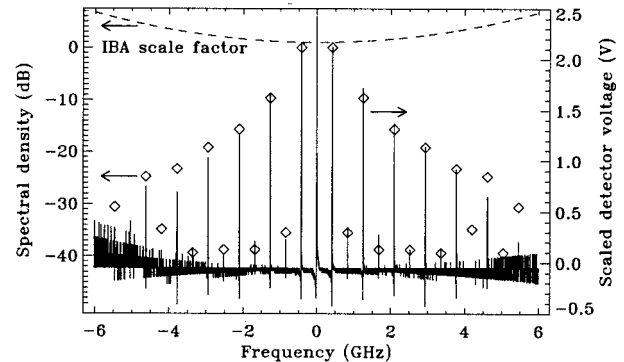


Fig. 2. Comparison of the scaled SHB spectrum analyzer detector voltages (solid curve) with the decibel peaks of the even-odd harmonics of the 420 MHz square wave measured by an electronic spectrum analyzer (diamonds). Dashed curve, the compensating IBA scale factor.

cused to a  $150 \mu\text{m}$  spot in the crystal. While the spectral features are continuously being burned into the IBA, we drive the piezo port of the readout laser (New Focus Vortex) with a 36 Hz,  $1.5 V_{pp}$  sinusoid, which provides a nonlinear optical readout chirp spanning approximately 80 GHz.

While the readout laser is nonlinearly chirping, we send a part of its output light ( $\sim 0.5$  mW) through the IBA at a slight angle to the writing beam to read the spectral features that were burned into the absorption band. This distorted spectrum-to-time mapping signal is detected with a differential homodyne technique, as shown in Fig. 1. The rest of the light from the chirping readout laser is passed through a 5.3 m long piece of polarization-maintaining fiber, whose end faces provide the 4% reflections that create a simple, low-finesse cavity with free spectral range  $\nu_F = c/(2nL) \approx 19$  MHz ( $n$  is the fiber's index and  $L$  is its length). The detected transmitted (or reflected) intensity provides a calibration signal whose accumulated zero crossings give us the information required for undoing the spectral distortion that is

present on the detected spectrum with a simple linear interpolation algorithm.

Figure 3 shows the spectral error of the peaks of the 420 MHz square wave's even and odd harmonics of both sidebands from  $-4$  to  $+4$  GHz and shows that the standard deviation of the error drops from 20 MHz before compensation (diamonds) to 0.8 MHz (solid curve) after compensation. The measured 1.8 MHz resolution of the spectrum analyzer is also indicated in the figure as a visual reference (dashed lines) and is apparently limited by the inherent instantaneous linewidth of the readout laser during the chirping process. Although we have not seen any problems in the data sets that indicate that the correction algorithm skipped one or more calibration cycles (owing to mode hops or excessive chirping errors), absolute frequency referencing could be achieved by use of either two quadrature signals<sup>12</sup> or multiple cavity lengths.<sup>13</sup>

When the detected voltages from our spectrum analyzer were plotted with the decibel powers of the signals measured by the electronic spectrum analyzer, a nearly exact correspondence was observed, indicating that in the saturated regime the hole's depth is nearly logarithmic with power. In addition, to further flatten the response of the SHB spectrum analyzer, the raw detected signals were scaled by the inverse of the inhomogeneous absorption band, which caused the frequency extremes of the read spectrum to rise (noticeable as the rising noise wings in Fig. 2). Although it is preliminary, this logarithmic response has the potential to increase the dynamic range of such an optical spectrum analyzer compared with previous acousto-optical spectrum analyzers. It should be noted that this material saturation effect in the IBA is completely different from saturation of the input time-domain signals in an acousto-optical or electro-optical modulator or in an electronic pre-amplifier. Time-domain saturation creates intermodulation product artifacts in the recorded spec-

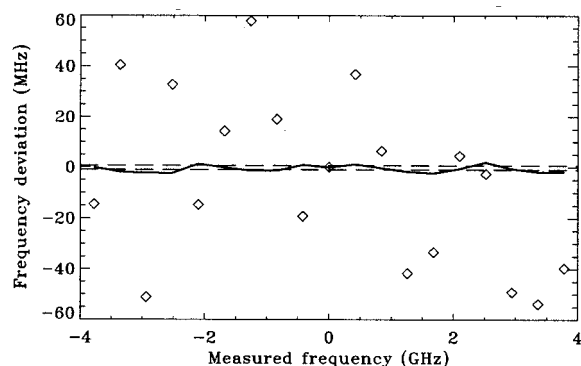


Fig. 3. Frequency error of the harmonic positions before (points) and after (solid curve) readout linearization. The standard deviation decreases from 20 to 0.8 MHz, which is below the system's 1.8 MHz resolution (dashed curve).

trum, which limit the spur-free dynamic range. In our IBA spectrum analyzer the saturation occurs in the spectral domain after channelization and does not create spectral intermods. Just as electronic spectrum analyzers have log amplifiers that provide the logarithmic output scale, one can regard the IBA's saturating response as a loglike amplifier.

We have presented experimental verification of a spectrum analysis technique that combines spectral hole burning with a spectroscopically calibrated readout technique to perform extremely wideband, unity-probability-of-intercept spectrum analysis. To our knowledge, the 5600 resolvable spectral bins covering 10 GHz of bandwidth represent the highest time-bandwidth product of any one-dimensional analog spectrum analyzer to date. Furthermore, it is nowhere near the limit of this approach, since a narrower-linewidth readout laser could increase the resolution to the material's 100 kHz linewidth, yielding nearly  $10^6$  spectral bins over 25 GHz.

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