

MICROWAVE SPECTRAL ANALYSIS USING OPTICAL SPECTRAL HOLEBURNING

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I. Abstract

A microwave spectrum analyzer capable of capturing multi-GHz spectra with sub-MHz resolution and unity probability of intercept based on optical spectral holeburning materials is proposed and initial demonstrations presented.

II. Introduction

The proliferation of electronic signals in battlefield environments poses a significant challenge to modern defense systems. Emerging radar systems must have the capability to detect and respond to multiple electronic signals that can be centered anywhere in the DC to tens of gigahertz range. Required response times are only a fraction of a second. While sophisticated hardware is available to lock on to signals over the microwave band given the sources center frequency, monitoring the full microwave band for signals of interest poses a major challenge. There is a growing need for RF spectrum analyzers that are capable of detecting unknown signals anywhere in the microwave band with sufficient certainty and precision to direct narrow band devices to the frequencies of interest.

In the past, GHz bandwidth acousto-optic spectrum analyzers (limited by acoustic generation and absorption) relied on the traveling-wave nature of acoustic propagation to diffract light at an angle proportional to RF frequency so that a Fourier lens could focus individual spectral components onto the pixels of an integrating 1-dimensional detector array. Recently, a spectrally-multiplexed diffraction analyzer was developed using spatial-spectral holography in which individual spectral components are again diffracted at an angle proportional to their frequency and focused onto a detector array [1]. This system operates analogously to the AO spectrum analyzer, but without any frequency limitation due to acoustics since the optical modulation is accomplished using an electro-optic modulator. This system could potentially operate at bandwidths of 10-20 GHz. However, since it uses spatial diffraction at

an angle proportional to frequency it uses up a spatial dimension, and is thus less suitable to 2-dimensional array applications.

In this paper we discuss an alternative and very simple topology for using spectral hole burning for microwave spectral analysis that uses just a single spot in an optical crystal, and is thus amenable to array applications. We propose the use of optical spectral holeburning materials as the means for performing spectral analysis on signals lasting less than a millisecond and producing the full spectrum over bandwidths up to 100 GHz with resolution on the order of a megahertz over the full bandwidth. We show initial demonstrations at low bandwidth, which show good dynamic range, and initial demonstrations at higher bandwidth, showing sub-MHz resolution of a 1 GHz bandwidth signal on an RF carrier that lasted only 100 microseconds.

III. Optical Spectral Holeburning

Spectral holeburning (SHB) materials act as multi-channel spectral analyzers. The individual ions doped in the crystal have narrow resonances, which can be on the order of a kilohertz at cryogenic temperatures (4-6 K). The crystals typically used are rare earth ions like Thulium (793 nm) or Erbium (1.5 microns) doped into oxides like YAG, which is a common laser material. Due to microscopic inhomogeneities in the crystal, the resonant frequency of each ion is slightly shifted (on the optical scale) from its nominal value. These shifts are randomly distributed and lead to a smooth inhomogeneous absorption profile that can be tailored to be from 20 GHz to over 200 GHz wide.

Spectral holeburning is the process of addressing only a small spectral subset of ions in the crystal by illuminating the crystal with a narrow band laser beam that only excites ions at the laser's resonant frequency. The absorption at the laser's frequency is reduced, creating a hole in the absorption profile that can be much narrower than the inhomogeneous linewidth, as shown in Figure 1.

The ratio of the inhomogeneous bandwidth to the homogeneous bandwidth yields the time-bandwidth

product of the processor. Ratios as high as 10^8 have been reported [2]. The depth of the hole in the absorption depends on the integrated power of the laser at the frequency of the hole. Multiple holes can be independently burned simultaneously, where the resultant absorption profile depends on the integrated power (optical energy) at each frequency. Thus, the power spectrum of the optical beam is recorded in the material, as long as the bandwidth of the modulated optical beam lies within the inhomogeneous absorption profile of the crystal.

This recorded power spectrum stored in the modified absorption profile persists for the population lifetime of the levels involved in the absorption transition, which is around 10 msec in both Thulium and Erbium. The modified SHB crystal's absorption profile can be scanned out within the population lifetime, yielding the power spectrum of the optical beam. Thus, the power spectrums of signals lasting on the order of tens of microseconds and with bandwidths ranging in the tens of gigahertz can be recorded and read out in about a millisecond with resolution on the order of megahertz.

IV. Spectral Analysis Operation

Figure 2 shows the basic components of the RF spectral analyzer. The RF input signal to be analyzed is modulated onto an optical carrier by a high bandwidth modulator, in this case an electro-optic phase modulator (EOPM). The optical carrier must have a linewidth less than the spectrum analyzer's required frequency resolution. Laser linewidths less than 10 kHz over the material's 10 ms lifetime are readily accomplished with a compact external cavity diode laser (ECDL) that is locked to a self-generated spectral hole in the same SHB crystal that is used to

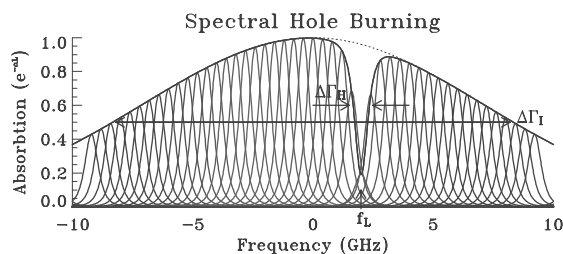


Figure 1: Inhomogeneous line with hole burned at f_L

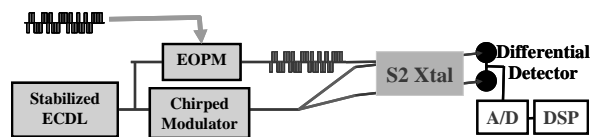


Figure 2: Basic components of the spectral analyzer based on optical spatial holeburning

perform the spectral analysis [3]. The modulated optical beam illuminates one spatial location on the SHB crystal and burns the power spectrum of the optical beam into the inhomogeneously broadened absorption profile of the SHB crystal at that spatial location. A typical spot size is on the order of 100 microns, thus a centimeter square crystal can analyze over 10,000 independent beams simultaneously.

A modified absorption profile is scanned out with a chirped optical beam [4] that here is shown created by modulating the same laser used in the processing stage, but could be done with a separate laser. In addition to probing the power spectrum burned in one spatial location, the chirped beam also probes a spot of the crystal that didn't experience any burning. This beam acts as the reference beam on a differential detector and enables a broad dynamic range of signals to be measured. The output of the differential detector is low bandwidth, less than a few megahertz, but contains the spectral information about the multi-gigahertz RF signal. The low bandwidth of the output signal allows the use of megasample per second analog to digital converters with 16 bits, which have dynamic ranges over 90 dB. Compression of the power spectrum by the SHB material and parallel channels with different attenuations could enable even higher dynamic ranges to be achieved.

V. Low Bandwidth Demonstration

A simple 1D spectrum analyzer was constructed using an acousto-optic modulator (AOM) to engrave a signal into the absorption profile of a Tm:YAG crystal, as illustrated in Figure 3. The output of a 793 nm laser diode is split into two paths; the first is used to lock the laser's frequency, as described below, while the second is used for spectrum analysis. This second beam is amplified to a power level of approximately 100 mW using a fiber-coupled tapered amplifier. The amplified beam then propagates through an acousto-optic modulator (AOM) to produce a diffracted output that is frequency shifted by an amount equal to the RF modulation frequency, ν_{rf} . The AOM produces four spectral features: Two strong tones, one weak tone, and one frequency swept tone, as shown in Figure 3. The AOM's DC order is blocked to prevent stray light from striking the crystal or the detector. The modulated beam propagates through the crystal, engraving holes at the spectral bins that correspond to the spectrum of the RF modulation. The crystal sits within a cryostat at a temperature of 4 K in order to prevent phonon broadening of the transition. This engraving process may be carried out repeatedly until the spectral bins reach saturation, at which point further engraving would distort the output.

Once the engraving process is complete, the AOM is modulated with a chirped RF signal generated by a low bandwidth arbitrary waveform generator. A low power beam propagates through the AOM, and the diffracted output strikes a detector located on the far side of the sample. As the chirp's frequency scans, the transmitted intensity will vary in a manner that corresponds to the signal spectrum.

Experimental results are presented in Figure 4, along with the signal spectrum as measured on a conventional RF Spectrum Analyzer, which was adjusted to have the same resolution bandwidth of 250 kHz. The experimental results have been normalized to account for the bandshape of the AOM. The resulting data are in excellent agreement with those collected from the RF Spectrum Analyzer, but for this frequency hopping signal, the conventional scanning spectrum analyzer had to be put in envelope and interpolation mode for many seconds in order to fill in all the gaps. In contrast, the optical spectrum analyzer gave a unity probability of intercept spectrum with better sensitivity in 10 msec.

VI. High BW demonstration

A high bandwidth proof of concept experiment was performed to demonstrate the ability of the material to analyze and resolve spectral content of microwave signals with unity probability of intercept. The crystal was set up to capture a 1 GHz bandwidth signal centered around 1.8 GHz. The experimental setup is shown in Figure 5. The high bandwidth input signal was created with a binary pulse pattern generator (PPG). The signal was a series of 40 square wave tones, each lasting 5 microseconds. The 40 tones were paired in intervals of 52.632 MHz with a pair spacing of 1MHz. Thus, the tones were 1.3000, 1.3010, 1.3526, 1.3536, . . . , 2.300, and 2.301 GHz. The spectrum was viewed on a conventional electronic RF spectrum analyzer if the sequence of tones is repeated continuously over the scan time of the analyzer. The RF spectrum recorded a series of 20 spikes when scanning from 1.2 to 2.4 GHz with a resolution BW of 10 kHz (sweep time 30s) (Figure 6a), where each spike can be seen to be a pair of spikes 1 MHz apart when scanning over 20MHz of the spectrum with a resolution BW of 1 kHz (sweep time 50 s) (Figure 6b).

The output of the PPG drove an electro-optic phase modulator (EOPM). Note that no down mixing of the signal is needed - this is true even when the signal is in the tens of gigahertz range, so long as the modulator bandwidth is not exceeded. The resultant optical signal contained the central optical carrier, two first order sidebands with the spectral content of interest, and higher harmonic sidebands introduced

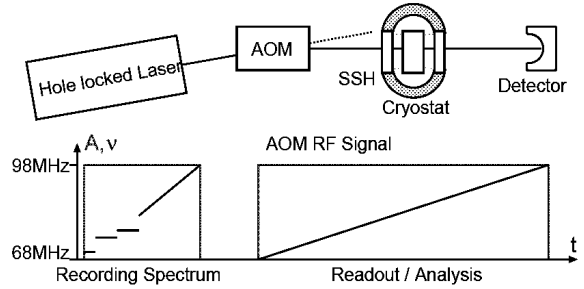


Figure 3: Spectrum analyzer based on spectral hole burning media. The diffracted order of an acousto-optic modulator (AOM) successively writes and reads changes in the absorption profile of an optical transition in a Tm:YAG crystal.

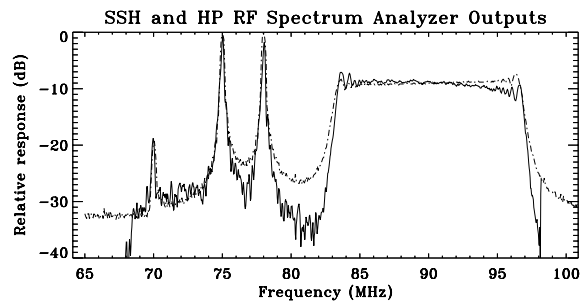


Figure 4: Signal spectra from the optical SHB spectrum analyzer demonstration (solid) and as measured by an HP Spectrum Analyzer (dashed).

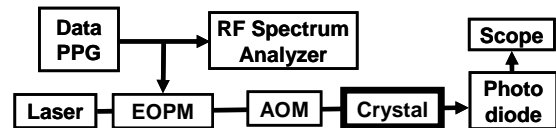


Figure 5: Set-up for high bandwidth demonstration.

by the binary coding and non-linearities in the EOPM. The two first order sidebands contain redundant spectral information, which is used in the readout technique below. An AOM allows the optical beam to pass only during the 100 microseconds of input signal and to blocks the beam when it is not modulated.

Once the SHB crystal records the double sideband spectrum of a single shot of the 100 μ sec signal, the spectrum is ready to be read out. The PPG, which was programmed with a digital chirp, drives the EOM to produce a double sideband linear frequency scan. This double-sideband chirp reads out the double sideband processed spectrum symmetrically and simultaneously. Increasing the output SNR by a factor of 2 compared to a single sideband configuration. The PPG was first programmed to scan from 1.2 Gbps to 2.4 Gbps. The

resulting readout signal is shown in Figure 6c. The plotted spectrum has only 18 spikes because even though the first two spikes were produced, they were not captured within the temporal window of the oscilloscope used to record the temporal output signal of the SHB spectrum analyzer. The horizontal axis has been converted from time to frequency.

With an identical processing stage and thus the same recorded spectrum, the spectrum was zoomed in on by varying the start and stop scan frequencies of the PPG's binary chirp. Different areas of the grating were probed to verify that any of the pairs

could be resolved in this way. Figure 6d shows a zoom in on the features around 2.3GHz, which include the tones at 2.300 and 2.301 GHz. A resolution of 200 KHz is observed.

It should be noted that in this initial proof-of-concept demonstration, an OD1.8 filter was placed in front of the detector to prevent saturation and reduced the signals by over a factor of 50. This attenuation will not be needed in future designs. Also, only a single detector was used. A dual detector with reference arm can significantly enhance the dynamic range.

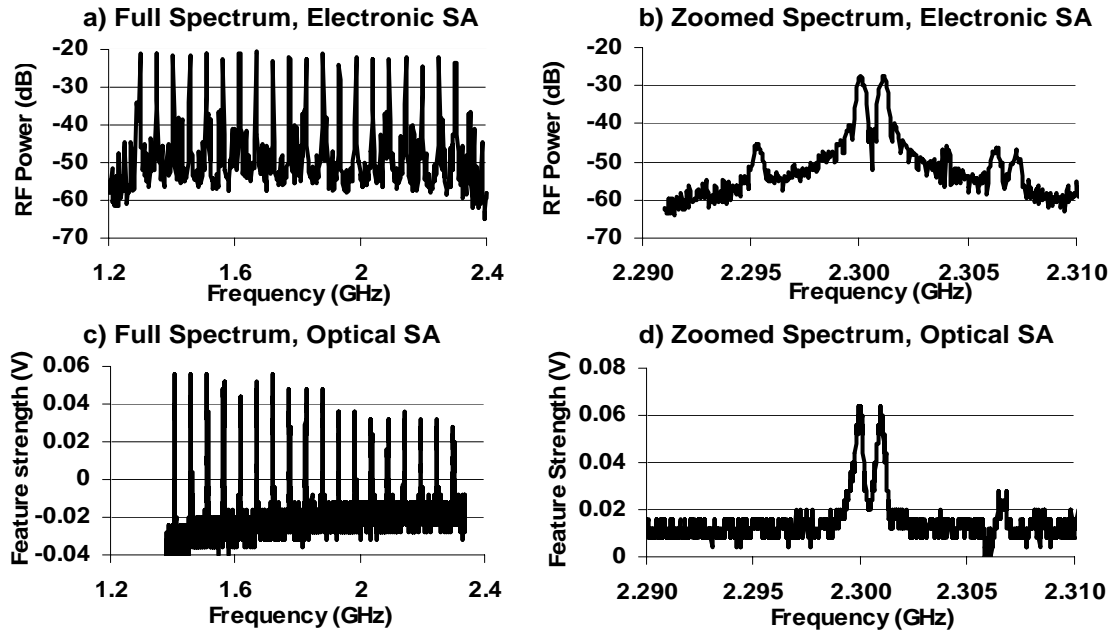


Figure 6. The full RF spectrum (a) and zoomed in RF spectrum (b) of the PPG waveforms are shown as analyzed with a conventional electronic spectrum analyzer (SA). The full spectrum (c) and zoomed in spectrum (d) are shown as analyzed by the spectral holeburning material after only a single occurrence of the waveform.

VII. Summary

Spectral analyzers based on spectral holeburning have the unique ability to capture waveforms that persist for less than a millisecond and to analyze their full spectrum up to 100 GHz with sub-MHz resolution. The spatial attributes of the SHB materials allows the extension of this technique to a 100% probability of intercept detector. Two preliminary demonstrations begin to show the potential of this technique: one showing greater than 40dB dynamic range and greater than 1 GHz processing. Both realized sub-MHz resolution. Further demonstrations are underway that will show significant increases in both dynamic range and bandwidth.

VIII. Acknowledgements

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IX. References

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