Broadband radio-frequency spectrum analysis in spectral-hole-burning media

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Spectral-hole-burning (SHB) media can be used for broadband radio-frequency spectrum analysis. This has shown with 20GHz bandwidth, sub-MHz resolution, and guaranteed interception of in-band signals. Recently demonstrated SHB spectrum analyzers have 40dB dynamic range and time-bandwidth products over 20,000, the highest that has been reported for analog one-dimensional spectrum analyzers. Further improvements could increase bandwidth to 100GHz and lower processing times to under a millisecond.

Radio-frequency (RF) spectrum is increasingly being used for a range of applications and this is placing tough demands on current spectrum analyzers. The military, for example, use high-performance spectrum analyzers for electronic warfare applications. Conventional electronic spectrum analyzers scan through the signal band, looking at only one frequency at a time. Emitters such as radars can avoid these spectrum analyzers by pulsing on and off or hopping from frequency to frequency. At the same time, the bandwidths that the analyzers must cover is expected to increase and their resolution is expected to increase too. The analyzers must also give low latency.

Optical spectrum analyzers can record all frequencies all the time so they will detect pulsed or hopping signals. Previous optical spectrum analyzers have been based on acousto-optics. They diffracted laser light at angles proportional to the RF spectrum and detected the Fourier-transformed beams on a CCD. They picked up every incident signal, but acoustic attenuation limited their bandwidth to about 1GHz.

Lorgeré et al. recently demonstrated a novel spectrum analyzer with a 3GHz bandwidth that used spectrally selective gratings written into an spectral-hole-burning (SHB) crystal. This mimicked the diffractive functionality of the acousto-optic spectrum analyzers but without the bandwidth limits.1

We are pursuing a simpler approach in which we record signal spectra directly in an SHB crystal. In our set-up, inhomogeneously broadened resonant absorbers act as a bank of integrating spectral radiometers. Probing the crystal with a chirp produces the signal spectrum, which can span 20GHz of bandwidth with 1MHz resolution and 100% probability of intercept.

SHB crystals consist of rare earth ions, such as Tm$^{3+}$ or Er$^{3+}$, doped into crystal hosts, such as YAG or LiNbO$_3$. The ions act as frequency-selective absorbers, with absorption linewidths under 100kHz at 2-4K. Because the ions are in different local environments, their absorption frequencies span an inhomogeneous bandwidth. In Tm$^{3+}$:YAG, this bandwidth is >20GHz, centered about a frequency of 378.2THz (793.3nm, a wavelength at which diode lasers are relatively inexpensive).2 A modulated laser beam, tuned to the resonance frequency, will burn holes in the crystal’s absorption spectrum. These spectral holes, which persist for about 10ms, are records of the modulation power spectrum. The crystal captures all spectral information in the inhomogeneous band with a resolution limited by the absorption linewidth and stores it for the spectral hole lifetime.

We recently demonstrated an RF spectrum analyzer using a Tm$^{3+}$:YAG crystal, as shown in Fig. 1. An electro-optically modulated laser beam burns a series of spectral holes into a single

Figure 1. RF spectrum analysis in spectral-hole-burning (SHB) crystals.

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spot in the crystal. Probing the spot with a chirped laser beam produces a temporal map of the spectral holes: as the chirp scans over a spectral hole, it experiences reduced absorption, which is detected as an increased signal. A second copy of the chirp beam at a different part of the crystal measures the crystal's background absorption. The differential detector subtracts the background signal from the information-bearing signal, and an oscilloscope saves the result. Retrieving the information stored in the crystal before the 10ms lifetime elapses requires scanning the chirp at MHz/μs rates. This means that we can use low-bandwidth, high dynamic-range detectors and digitizers to measure broadband signals. A typical output spectrum is shown in Fig. 2.

We generate the chirp beam by tilting the external grating of an external-cavity diode laser (ECDL) with a piezoelectric transducer, as shown in Fig. 1. Inevitable imperfections in the grating's motion mean that the frequency of the beam produced does not quite change linearly with time. Instead of trying to produce a perfectly linear chirp, we measure chirp nonuniformities with a fiber etalon (not shown).

The etalon transmits peaks that are aperiodic in time, but evenly spaced in frequency. We correct the detected spectrum using the measured aperiodicity to create a linearized frequency map.

Readout with a chirp of rate $\kappa$ (in Hz/s) yields a signal power spectrum (blurred by the homogeneous linewidth) that is convolved with a chirp. The coherently-detected field is multiplied by a chirp. For a resolution of 1MHz, we can neglect the convolution for $\kappa$ under 1MHz/μs. Interrogating 20GHz in under 10ms means that $\kappa \geq 2$MHz/μs. This produces spectral features blurred by ringing—the effects of the convolution with the chirp. Chang et al. recently showed that deconvolving the detected field with another copy of the chirp removes deleterious ringing, allowing us to interrogate spectral holes at rates faster than the Fourier resolution limit. We could also read the holes with a chirped frequency comb, with each comb order interrogating 100s of MHz in 100s of microseconds. Spectrally channelizing the comb with a grating or etalon would spatially separate the orders; the separated orders could then be detected on a detector array.

Switching from Tm$^{3+}$:YAG to Er$^{3+}$:LiNbO$_3$, could increase the analysis bandwidth to as much as 100GHz (as limited by electro-optic modulation bandwidth) and move the resonance wavelength to 1531.5nm, conveniently located at the edge of the telecommunications band. In addition, each crystal can accommodate hundreds of channels in different spots simultaneously, enabling massively parallel processing for phased array antennas.

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