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Laser linewidth narrowing using transient spectral hole burning

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ABSTRACT

We demonstrate significant narrowing of laser linewidths by high optical density materials with inhomogeneously broadened absorption. As a laser propagates through the material, the nonlinear spectral hole burning process causes a progressive self-filtering of the laser spectrum, potentially reaching values less than the homogeneous linewidth. The transient spectral hole dynamically adjusts itself to the instantaneous frequency of the laser, passively suppressing laser phase noise and side modes over the entire material absorption bandwidth without the need for electronic or optical feedback to the laser. Wide bandwidth laser phase noise suppression was demonstrated using Er^{3+} doped Y_2SiO_5 and $LiNbO_3$ at 1.5 μm by employing time-delayed self-heterodyne detection of an external cavity diode laser to study the spectral narrowing effect. Our method is not restricted to any particular wavelength or laser system and is attractive for a range of applications where ultra-low phase noise sources are required.

1. Introduction

Narrow linewidth lasers with low phase noise are required for many applications in optical metrology, long-baseline interferometry, coherent sensing and detection, and ultra-high resolution spectroscopy of atoms and molecules. For example, in the arena of quantum information storage based on rare-earth-doped materials, the laser linewidth must be comparable to the linewidth of the atoms in order to manipulate their coherent quantum superposition states or to map quantum information from light onto the material [1]. Also, to fully exploit the capabilities of rare-earth materials in powerful spatial spectral holography optoelectronic devices requires precision frequency addressing that is greatly improved by using low phase noise narrow-band frequency-stabilized lasers.

To provide narrow-band sources, diode lasers offer an attractive low cost alternative to solid-state and fiber lasers, but their linewidths are dominated by large amounts of phase noise extending out to the gigahertz range due to spontaneous emission, large cavity linewidths, and carrier-density fluctuations in the p-n junction [2]. This phase noise can directly affect low-bandwidth measurements since heterodyne between the high-frequency components contributes low frequency noise to the measured laser intensity.

To improve the free-running linewidth of external cavity diode lasers, we have demonstrated that, for many spectral hole burning (SHB) applications, stabilization to a regenerative transient spectral hole provides the necessary frequency stability [3,4]. This approach supplies an automatic frequency match by virtue of stabilizing the laser to the same transition that is also being used for the application. Moreover, both the signal processing and laser frequency stabilization crystals experience the same local environment in the cryostat and hence vibrations, temperature fluctuations, and other environmental noise sources become common mode and do not affect the relative stability. The resulting improved laser performance was a major breakthrough for spectroscopic and device applications [3,5–7].

Although a transient spectral hole frequency reference is modified by the probing laser itself as the hole is continuously regenerated, it serves as an integrator, or “optical flywheel,” that provides an error signal that can be used to correct rapid laser frequency excursions; however, laser frequency drift may still occur for periods longer than the spectral hole lifetime, typically on the order of several milliseconds. Since many SHB applications require laser frequency stability on this exact timescale, stabilizing the laser to a transient spectral hole has been extremely useful. If improved medium-term stability is required, persistent spectral holes with longer lifetimes (up to weeks) may be employed as references [8]. Recently, this approach has been used at NIST to achieve an impressive laser frequency stability of 6×10^{-16} over timescales of seconds [9].

To provide long-term frequency stability, the inhomogeneous absorption line of the SHB material can be incorporated as a fixed absolute frequency reference, either by itself [10] or in a hybrid approach where the feedback error signal from a transient spectral hole is combined with an additional error signal derived from the inhomogeneous line that acts as a low-gain absolute frequency reference [5]. This approach was successfully demonstrated with

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a 130 MHz wide inhomogeneous line in Er^{3+}:$LiYF_4$, [10] and with both a spectral hole and a 500 MHz wide inhomogeneous line in Er^{3+}:Y_2SiO_5 using the hybrid technique [5]. In the case of hybrid-locking in Er^{3+}:Y_2SiO_5, we were able to control long-term drift to ~10 kHz/min, but frequency excursions of ~10s of kHz over a few seconds were still present due to the fairly large 500 MHz inhomogeneous line of the particular Er^{3+}:Y_2SiO_5 crystal used in this demonstration, which consequently limited the gain for electronic feedback. Using the sharper 130 MHz wide inhomogeneous line in Er^{3+}:$LiYF_4$, laser frequency drift was reduced to less than 1.4 kHz/min [10].

Active electronic stabilization is only capable of suppressing laser phase noise within the bandwidth of the servo feedback loop (up to a few megahertz at most), and high frequency noise outside the electronic bandwidth remains uncorrected in the laser's frequency spectrum due to the inherent time delays in the servo feedback loop. To overcome these limitations, we describe a new SHB self-filtering technique that strongly suppresses high frequency laser phase noise, providing narrow-band sources especially well-suited for SHB and interferometric applications. This new passive filtering approach perfectly complements the capabilities of the active frequency stabilization techniques described above without need for additional electronic or optical hardware.

2. Using transient spectral hole burning as a dynamic laser phase noise filter

Spectral hole burning in rare-earth-doped materials is ideally suited for many applications since it allows the inhomogeneous absorption line to be modified in a controlled fashion. It has long been recognized that this capability can be exploited to generate spectral filters by preparing narrow transmission windows within the absorption lineshape [11,12]. This led to a number of applications where fixed spectral holes generated by a narrow-band pump laser have been used to selectively filter broadband signals [13–15]. This idea has also been applied to provide filtered optical feedback to the laser cavity itself, significantly improving the laser linewidth and reducing phase noise [16].

Recently, we have proposed an alternate approach for wide bandwidth laser phase noise suppression and laser linewidth narrowing that exploits the non-linear nature of SHB for an optically thick material [17,18]. Rather than employing a spectral hole as a linear filtering element analogous to traditional Fabry-Pérot cavity filtering [19] or feedback [20], our method is a non-linear “self-filtering” propagation effect that is unique to inhomogeneously broadened SHB materials. To the best of our knowledge, this SHB passive self-filtering process has not been observed before and is particularly simple to implement compared to other SHB-based techniques since it does not require any electronic or optical feedback to the laser. The self-filtering effect may be easily understood by considering the evolution in the laser power spectrum and spectral hole shape as narrow-band light propagates through a high optical density SHB material. As the single mode laser enters the material, the laser burns a spectral hole corresponding to its power spectrum into the inhomogeneously broadened absorption line. The spectral hole preferentially transmits light near the peak of the laser's power spectrum while absorbing light in the tails where the hole burning transition is not saturated. Hence, as the laser light penetrates deeper into the SHB material, its linewidth is continuously reshaped, becoming progressively narrower as the phase noise is suppressed by the nonlinear absorption process of the medium. At the same time, as the laser spectrum continues to become narrower while propagating through the material, it burns a correspondingly narrower spectral hole that provides an even greater degree of filtering. Since this effect is based on transient SHB, the frequency of the spectral hole automatically tracks the instantaneous laser frequency, maintaining a high optical transmission at the peak of the laser power spectrum. Laser phase noise is suppressed by as much as the optical density of the material (OD of >100 can be achieved in ~centimeter sized crystals) over the entire material absorption bandwidth (up to >100 GHz) and the laser linewidth can potentially be reduced to less than the spectral resolution of the material (down to <100 Hz) due to the nonlinearity of the propagation [17,21,22]. Furthermore, since the SHB process depends on the intensity of the light in the crystal, the same filtering effect may be obtained over a wide range of laser powers by choosing a laser spot size in the crystal that results in the optimum intensity. Our method offers great advantages if combined with active laser frequency stabilization as it efficiently suppresses all remaining noise on the laser beyond the bandwidth of the electronic servo loop up to the bandwidth provided by the material.

3. Experimental

We have demonstrated the SHB laser phase noise suppression technique at telecom wavelengths near 1.5 μm using 0.02% Er^{3+}:Y_2SiO_5, 2% Er^{3+}:Y_2SiO_5, and 0.1% Er^{3+}:$LiNbO_3$ crystals. The crystals were mounted in a liquid helium bath using an Oxford Spectromag cryostat. The optical transition employed is between the lowest energy $^4I_{15/2}$ and lowest energy $^4I_{13/2}$ states of the $4f^{11}$ configuration. In Er^{3+}:Y_2SiO_5 and Er^{3+}:$LiNbO_3$, the peak absorption in zero magnetic field occurs at 1536.48 nm and 1532.06 nm, respectively [23,24]. To observe the strongest noise suppression effect, a high optical density SHB filter material is preferred, so we used a 2 mm thick 2% Er^{3+}:Y_2SiO_5 crystal with its absorption spectrum shown in Fig. 1. Because this crystal has a very high optical density that cannot be directly measured accurately, the lineshape was determined by using the thermally depopulated transition at a high field of $B=3.5$ T and then the absorption coefficient was scaled to full population using the known transition oscillator strength and crystal concentration. For the SHB laser linewidth narrowing experiments, we used the polarization direction of $\mathbf{E}\parallel\mathbf{D_1}$ with a lower optical density of 17 ($\alpha L=39$). We also obtained useful results using a 0.02% Er^{3+}:Y_2SiO_5 crystal with a smaller optical density of 3.1. That crystal had a peak optical absorption coefficient of 50 cm^{-1} when the light was propagated along the 1.43 mm thick **b** direction at a magnetic field of $B=5$ T along $\mathbf{D_1}$ and $\mathbf{E}\parallel\mathbf{D_2}$.

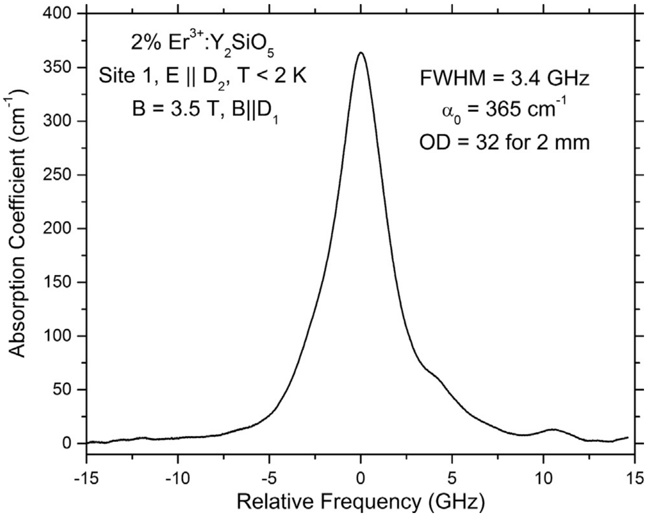

Fig. 1. Laser absorption spectrum of 2% Er^{3+}:Y_2SiO_5 at a magnetic field of $B=3.5$ T with $\mathbf{B}\parallel\mathbf{D_1}$ and $\mathbf{E}\parallel\mathbf{D_2}$ at liquid Helium temperature.