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Programmable laser frequency stabilization at 1523 nm by use of persistent spectral hole burning

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Diode laser frequency stability of 2 kHz to 680 Hz over 20 ms to 500 s has been demonstrated at 1523 nm in the technologically important communication band by use of persistent spectral holes in the inhomogeneously broadened $^4I_{15/2} \rightarrow ^4I_{13/2}$ optical absorption of $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$. Laser frequency stabilization was realized without vibrational or acoustical isolation of either the laser or spectral hole frequency reference, providing the means for implementing a versatile, compact, stable source. © 2003 Optical Society of America


Persistent spectral holes can have lifetimes ranging from several weeks to months or longer; consequently, they can serve as long-term secondary frequency standards. Compact vibration-insensitive laser stabilization in regenerative spectral hole burning materials1–4 was recently reported, and a persistent spectral hole frequency reference was demonstrated.5 Here we report improved performance to longer integration times for diode lasers stabilized to persistent spectral holes at 1523 nm in $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$, which we believe is the first example of a programmable frequency reference material in the spectral region at 1.5 $\mu$m. Although the ideal persistent spectral hole-burning material at 1.5 $\mu$m is not yet available, these results highlight the concept of using a persistent spectral hole for laser frequency stabilization.

Many scientific and device applications require frequency stability at the achieved and anticipated levels. Lasers stabilized to spectral holes already find important application in coherent transient spectroscopy and optical devices6,7 and are a key component of optical correlators with improved time–bandwidth products.8 Besides applications related to spectral hole burning, simple stable laser systems such as ours, which does not require vibration or acoustic isolation, open up 1.5–$\mu$m technology for a new variety of uses, such as eyesafe laser radar, remote vibrometry, and interferometry in the field. Anticipated system performance will extend the use to ultrahigh-resolution spectroscopy, quantum optics research, electromagnetically induced transparency, optical clocks, metrology, and other applications requiring ultranarrowband light sources or coherent detection.

The material $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$, to our knowledge, is the only material yet known to show persistent spectral hole burning at 1.5 $\mu$m.9 Deuteride (D−) ions introduced into a 0.05-at.% $\text{Er}^{3+}$-doped $\text{CaF}_2$ crystal both interstitially and by substitution for F− ions in the vicinity of $\text{Er}^{3+}$ ions give rise to additional $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$ absorption lines. The lines at 1523 nm from the $R$ center exhibit persistent hole burning by optically induced D− ion migration. Spectral holes of full width at half-maximum (FWHM) of $\sim$40 MHz showed no measurable degradation over 48 h.9 The activation energy deduced from those results suggests that the hole lifetime could be indefinitely long for samples held at liquid helium temperature. The material $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$ should be practical as a frequency reference up to a temperature of 15 K where the hole width reaches 200 MHz (FWHM), and that permits simpler operation with a cryocooler. Wavelength versatility can be achieved by replacement of the $\text{Er}^{3+}$ ions with other rare-earth ions, since the hole-burning mechanism is a property of the host, rather than being dopant specific.10,11

Figure 1(a) shows a transmission spectrum of $\text{Er}^{3+} \cdot \text{D}^- \cdot \text{CaF}_2$ and illustrates a number of spectral holes programmed in the inhomogeneous absorption line of the $R$ center. Laser beat frequencies, pulse spectra, holograms, or data can be recorded and read.
Laser frequency stabilization was implemented with FM spectroscopy for sensing the center of a spectral hole in much the same way as for a Fabry–Perot frequency reference. The experimental setup was similar to that previously reported. Two independent external cavity diode lasers were phase modulated with modulation index of $M = 0.4$ and modulation frequencies of 93 MHz and 109.5 MHz, respectively, values chosen to lie well outside the ~40 MHz (FWHM) spectral holes. Figure 1(b) shows a transmission spectrum through a single spectral hole and the corresponding demodulated FM error signal [Fig. 1(c)]. The diode laser injection current and piezodriven feedback prism plate provided fast and slow frequency corrections. Stable laser and modulator systems—each 10 cm × 20 cm—and the optical cryostat, locking electronics, and laser diagnostics were fitted on a tabletop breadboard without vibrational or acoustical isolation. Miniaturization of this apparatus is feasible with waveguide-based external cavity diode lasers and electro-optic modulators, leading to a compact system with size limited by the required cryocooler.

Each laser was independently stabilized to a separate reference crystal immersed in a single cryostat at $T = 1.9$ K. Since the width and depth of the programmed persistent spectral hole determine the slope of the error signal for active laser frequency stabilization, careful preparation of the initial persistent spectral hole was important. An increase in hole width as a function of burn time was observed, resulting from the longer hole-burning time for ion centers having only partial frequency overlap with the laser and consequently a lower effective transition probability than centers that are resonant with the laser. This result implies a trade-off between hole depth and hole width, limiting the error signal slope and signal-to-noise ratio of detection. Good locking results were achieved with persistent holes of ~40 MHz (FWHM) and a depth corresponding to a change in transmission by ~5%, prepared by illumination of the sample for 20 s with incident light intensities of ~300 $\mu$W/cm$^2$. Since the hole width was much wider than the unstabilized laser linewidth, no active stabilization was required during hole preparation. For materials with narrower persistent spectral holes, it will be necessary to reduce the laser linewidth by bootstrapping of the hole burning and stabilization procedure. Minimizing continuous modification of the hole while maintaining a good signal-to-noise ratio on the locking detector during active stabilization required a beam spot diameter of 4.8 mm and a low irradiance of ~30 $\mu$W/cm$^2$ at the sample. An additional factor of 20 in signal-to-noise ratio should be achievable with a larger illuminated area of ~20 mm.

Laser frequency stability was characterized by use of the Allan deviation of the beat frequency between the two lasers. Figure 2 contrasts measurements for the free-running lasers with those for the lasers stabilized to spectral holes. The free-running lasers already show excellent frequency stability sufficient for many applications. With the lasers locked to the ~40 MHz (FWHM) persistent spectral holes, an improvement of more than 3 orders of magnitude was achieved for integration times greater than 300 s, whereas an order of magnitude was achieved for integration times of 2 ms. Allan deviations down to 680 Hz were attained over a wide range of integration times without requiring vibration isolation of the laser or the crystal frequency reference, demonstrating laser frequency stabilization to better than 6 parts in $10^8$ of the ~40-MHz hole width.

Characterization and optimization of spectral hole-burning references by experiment and simulation have shown that the Allan deviation over short integration times is determined by the width of the spectral hole, whereas stabilization over long integration times is determined by the lifetime of the spectral hole. In Er$^{3+}$:D$^-$:CaF$_2$ the stability over short (<$10^{-7}$ s) integration times is limited by the relatively low gain of the reference arising from the broad hole and the reduced laser power used to probe it. Nevertheless, the long lifetime of the persistent Er$^{3+}$:D$^-$:CaF$_2$ spectral holes leads to good medium- and long-term stability demonstrated in Fig. 3, where the change in beat frequency between the (a) free-running and (b) actively stabilized laser is shown. Laser frequency drift has been reduced to only a few kilohertz per minute, limited in this implementation by modifications of the spectral hole by continuous exposure to the probing laser. All Allan deviation values increased by ~100 Hz over a period of 10 min because of this process. Limiting the exposure of the spectral hole by decreasing the irradiance or periodically (rather than continuously) probing the reference could substantially improve the performance. The long-term stability of the persistent spectral hole itself is primarily limited by temperature fluctuations. A measured frequency shift of the hole with temperature of 1.6 kHz/K at 1.5 K implies hertz stability of the reference if the temperature is maintained at the millikelvin level.

![Figure 2](image-url)

**Fig. 2.** Allan deviation for the heterodyne beat frequency between two lasers: (a) free-running (triangles), (b) independently locked to persistent spectral holes in the $4f_{15/2} \rightarrow 4f_{13/2}$ transition in Er$^{3+}$:D$^-$:CaF$_2$ at 1523 nm (circles). Filled symbols, 300 sample Allan deviations measured directly by a frequency counter; open symbols, values computed from the beat-frequency data (cf. Fig. 3).
Fig. 3. Change in heterodyne beat frequency between (a) free-running lasers and (b) lasers independently locked to persistent spectral holes in separate crystals over a period of 10 min, (c) expanded view of data shown in (b). The counter gate time was 50 ms.

The material Er$^{3+}$:D$^-$:CaF$_2$ is not ideal but illustrates the concept of using a persistent spectral hole for laser frequency stabilization. Development of persistent hole-burning materials with lower quantum efficiency for hole burning and with narrower hole widths should significantly improve performance. Gated spectral hole-burning materials are being designed to eliminate continued hole burning$^{15}$, a gated hole-burning material requires a second laser field or physical process for hole burning to occur and is therefore impervious to hole burning during reading. Technical limitations were also set by thermally dependent residual amplitude modulation at the electro-optic modulator and by voltage offsets in the feedback loop that added to long-term laser drift.

In conclusion, we have extended the use and performance of persistent spectral holes as programmable laser frequency references to the important 1.5-μm optical communication window, achieving subkilohertz laser frequency stability over broader time scales. A compact laser frequency stabilization system that utilizes inexpensive diode lasers has been demonstrated. The system is not limited to low optical power applications, since Er-doped fiber amplifiers or injection-locked high-power laser diodes can be used to boost the output power to several watts or more.

Additional, more suitable spectral hole-burning materials for laser frequency stabilization and spectral hole burning—based optical processing are under constant development and span a wide wavelength range, facilitating the stabilization of other sources and proving the versatility of the technique.

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