Room-temperature spectral hole burning in an engineered inhomogeneously broadened resonance

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We observe spectral hole burning in a room-temperature optical fiber pumped by a spectrally broadened pump beam. This beam drives the stimulated Brillouin process, creating an inhomogeneously broadened resonance in the material whose shape can be engineered by tailoring the beam’s spectrum. A monochromatic saturating beam “burns” a narrow spectral hole that is 10⁴ times narrower than the inhomogeneous width of the resonance. This research paves the way toward agile optical information processing and storage using standard telecommunication components. © 2008 Optical Society of America

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Spectral hole burning occurring in an inhomogeneously broadened optical transition can be used for extremely high-density data storage [1]. In frequency-selective data storage (FSDS), a monochromatic laser beam saturates the absorption over a narrow spectral range whose minimum width is governed by the homogeneous linewidth of the transition (Δν_H). Multiple bits are written by accessing different homogeneous classes of transitions within the inhomogeneous profile (width Δν_I), where the number of bits that can be stored at each spatial location within the recording medium is Q ~ Δν_I/Δν_H.

Time-domain approaches to FSDS [2–4], where the entire spectrum of an optical data stream is stored in parallel within the inhomogeneous profile, can achieve very high input–output rates (~Δν_I) while maintaining high storage densities [5]. Variations on this approach are being investigated for quantum memories [6] and for microwave photonic signal processing functions [7,8]. These systems often rely on the narrow homogeneous transitions (Δν_H ~ 100 kHz) found in cryogenically cooled crystals doped with rare-earth ions, where Δν_I can exceed 25 GHz. For these applications, Q is an important metric specifying the selectivity or capacity of the device.

In this Letter, we demonstrate spectral hole burning in an inhomogeneously-broadened resonance arising from stimulated Brillouin scattering (SBS) in an optical fiber pumped by a spectrally broadened laser. The observed width of the spectral hole is less than 50 kHz using a monochromatic saturating (hole-burning) beam. The inhomogeneous profile can be tailored by engineering the pump spectrum, which can, in principle, extend over the entire transparency range of the material.

Before discussing our results, we briefly describe the SBS process [9]. Consider a situation where a nearly transparent material is illuminated by an intense monochromatic pump beam at frequency ν_p and a weak probe beam at frequency ν_p. Through the process of electrostriction, these waves induce a high-frequency acoustic excitation (frequency Ω_p), which modulates the dielectric constant. In turn, the modified dielectric constant couples to the light fields, causing energy transfer between them. The probe field is amplified most efficiently when it counter-propagates with respect to the pump field, thereby phase matching the three-wave interaction, and when ν_p = ν_d − Ω_p, which resonantly excites the acoustic wave. The resonance width (FWHM) is denoted by Ω_B and has a typical value of 20–50 MHz for standard silica single-mode optical fibers.

One key point underlying our work is the prediction [10,11] that a narrow spectral hole can be burned in the homogeneous SBS gain profile using an intense monochromatic probe beam. The hole arises from depletion of the pump beam and has a width ~1/τ_r, where τ_r is the transit time of light through the material. With the availability of highly transparent optical fibers with lengths well exceeding 1 km, such a spectral hole could be much narrower than 100 kHz. Narrowband spectral hole burning in inhomogeneously broadened, self-generated SBS has been observed previously, where thermally scattered broadband emission is amplified to such an extent that it can burn a spectral hole and simultaneously probe the hole [12].

For the homogeneously broadened case, the potential value of Q is limited to the ratio of the width of the resonance (~50 MHz) to the width of the hole, or Q < 500. To dramatically increase Q, we broaden the SBS gain spectrum by broadening the spectrum of the pump laser [13,14]. Here, the SBS gain spectrum experienced by a weak probe beam is simply the convolution of the pump spectrum with the SBS spectrum obtained for a monochromatic pump beam [15].

We show below that the spectral broadening does not disrupt the hole-burning process predicted in [10,11]. This effect arises because the broadened...
resonance consists of essentially independent spectral channels whose width is comparable with $\Gamma_B$. The spectral channel whose frequency is closest to a intense monochromatic probe beam experiences hole burning.

In our experiment, we use a commercially available small-core single-mode optical fiber (OFS, HNLF) of length $L=2$ km, Brillouin gain coefficient $g_B=1.8 \times 10^{-11}$ m/W, $\Omega_B=9.6$ GHz, $\Gamma_B=50$ MHz, and effective SBS length, refractive index, and mode area $L_{\text{eff}}=1.6$ km, $n_{\text{eff}}=1.5$, and $A_{\text{eff}}=11 \mu m^2$, respectively. The fiber is pumped by a distributed-feedback laser (Sumitomo, SLT5411-CC) operating at a wavelength $\lambda=13$ MHz (2), and 175 MHz (3). (c) Single-sided hole burning of a small-core single-mode optical fiber (OFS, Zehnder modulators from the setup and directly modulating the intensity of the Agilent laser with the sinusoidal reference voltage generated by our lock-in detector. This procedure creates a beam with a central carrier frequency (the saturating beam) and two weak sidebands (serving as symmetric probe beams). Figure 1(c) shows a portion of the one-sided spectral profile of the hole for three values of $P_s$. As $P_s$ increases, the hole becomes deeper and its width broadens. An accurate determination of the hole width is not possible with this detection method, because we cannot collect data down to zero frequency. However, it is clear that the FWHM width of the hole is no greater than 80 kHz (160 kHz) for the intermediate (high) value of $P_s$.

To circumvent the issues related to our frequency-domain detection methods, we conduct a time-domain measurement using a single saturating beam whose power is adjusted from a power that is so low ($P_{\text{low}}$) that it does not substantially saturate the resonance (i.e., does not burn a hole) to a value

Figure 1(b) shows the observed SBS gain spectrum, defined as $\ln(P_{\text{out}}/P_{\text{in}})$, where $P_{\text{out}}$ ($P_{\text{in}}$) is the output (input) power of the weak tunable probe beam, for three values of $\nu_s$ and $P_d=17$ mW. For $P_d=0$, the SBS amplifying resonance has a width (FWHM) of $\sim 460$ MHz and is nearly Gaussian shaped, which gives $\Delta \nu_1$. With $P_d=100 \mu W$, a deep spectral hole is burned in the resonance profile that tracks $\nu_s$. The width (FWHM) of the holes is $\sim 7$ MHz, which is much narrower than $\Gamma_B$. This result demonstrates the potential ability to burn independent spectral holes throughout the inhomogeneous resonance. The resolution of our measurement is $\sim 3$ MHz, dictated by our frequency scan rate and lock-in amplifier time constant.

Noticeable is a peak in the center of each hole, and that the hole dips below unit transmission for case 2. These features are an artifact of our lock-in detection method and arise from the beating between the saturating and probe beams, which passes through the lock-in amplifier when their frequencies are comparable (within the resolution) with the chopping frequency.

To improve the resolution of our measurement, we use a different modulation technique that is effective when $\nu_s$ is set to the center of the SBS gain resonance [16]. The method involves removing the Mach–Zehnder modulators from the setup and directly modulating the intensity of the Agilent laser with the sinusoidal reference voltage generated by our lock-in detector. This procedure creates a beam with a central carrier frequency (the saturating beam) and two weak sidebands (serving as symmetric probe beams).

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Ps,high), that is high enough to cause saturation, and then back to Ps,low. In this way, we can directly measure the time-dependent creation and refilling of the spectral hole, with exponential time constants denoted by τc and τr, respectively. The width of the spectral hole is inversely related to τc. For these experiments, the inhomogeneous width was increased to 760 MHz and Pd=28 mW; these changes do not affect significantly our findings.

Figure 2(a) shows the temporal evolution of the transmitted saturating-beam power Pout for various values of Ps,high when νs is set to the center of the broadened SBS resonance. As the input power switches to Ps,high, it is seen that the transmitted power first attains a high value (the hole is not yet formed) then decays exponentially to a lower, steady-state value, indicating that the hole has been created. When the probe power switches to Ps,low, the power initially is low, indicating the hole continues to persist, then exponentially increases to a steady-state value, indicating the hole has filled.

We fit the data to exponential functions to extract τc and τr, which are shown in Fig. 2(b) for various values of Ps,high with Ps,low held approximately constant. It is seen that τc decreases (the hole broadens) as Ps,high increases because higher input probe powers can more quickly deplete the pump power, thereby saturating the SBS process more quickly. On the other hand, τr remains nearly constant, because we keep Ps,low approximately constant.

The time constants are much longer than the acoustic lifetime $1/2\pi T_B=3.2$ ns and comparable with the transit time through the fiber $t_s=(n_{\text{eff}})l/c=10.2$ μs. From our measurements of τc, we infer a spectral-hole width $\Delta\nu_H$ between 33 and 94 kHz depending on Ps,high. These values are consistent with our frequency-domain measurements shown in Fig. 1(b).

Based on our measurements, we find that $Q\sim 10^4$. This value can be increased easily by further spectral broadening (a width of 25 GHz has been observed recently [17]) or by using several pump lasers whose frequencies span the entire transparency range of the fiber (bandwidth exceeding 1 THz). This system will likely find the greatest application in photonic signal processing where a brief saturating pulse would prepare the medium, which would effect for a time $\sim t_r$ subsequent pulses that pass through the medium.

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