Loop-mirror filters based on saturable-gain or -absorber gratings

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We present a novel all-fiber narrow-band filter based on pump-induced saturable-gain or -absorber gratings in a loop mirror. Our design provides built-in interferometric phase alignment of the signal to the grating for optimal filtering. Notch or bandpass functionality is determined by the choice of gain or absorption and the input ports selected for the pump and signal. The loop-mirror filter has potential bandwidths from the submegahertz to beyond the gigahertz regimes, and one can tune it optically by changing the wavelength of the pump light that establishes the grating. Such filters have potential applications to wavelength-division-multiplexed optical networks and optical rf signal processing. © 1999 Optical Society of America

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Tunable narrow-band optical filters are becoming increasingly important for a variety of different applications, such as supporting large numbers of closely spaced channels in dense wavelength-division-multiplexed optical networks. Additionally, narrow-band optical filters are useful for manipulating individual subcarrier-multiplexed channels within the optical domain and in photonic links that engage in high-speed optical rf signal processing or that require tunable narrow-band rf receivers. Common filter technology available for such applications includes arrayed waveguide gratings, thin-film dielectric interference filters, conventional fiber Bragg gratings, and fiber Fabry–Perot filters.[1] However, these devices have difficulty providing either notch or bandpass filters with bandwidths less than 1 GHz. These approaches also suffer from one or more of the following disadvantages: (i) operation only at fixed wavelengths or over a limited range, (ii) requirement for mechanical or temperature tuning and temperature sensitivity, (iii) nonfiber design and large insertion loss, and (iv) periodic passbands.

Experiments were performed previously with erbium-doped fiber (EDF) as a saturable medium in a non-loop-mirror design to create simple light-induced Bragg reflection filters, but these filters did not account for the phase relationship between the signal and the pump-induced grating.[2–4] However, bandpass filters based on saturable-absorber gratings have been shown to be effective for laser linewidth narrowing.[5–8] More recently, self-filtering of signals[9] and fiber-laser frequency control[10] have also been demonstrated by use of saturable-absorber gratings.

We analyze and demonstrate a novel design for all-fiber tunable notch and bandpass loop-mirror filters (LMF's) with bandwidths ranging from the submegahertz to beyond the gigahertz regimes. Our narrow-band LMF uses a straightforward configuration based on a loop mirror containing a saturable-gain or -absorber section. The LMF results from a grating that is formed by spatial hole burning in an active medium, induced by the interference pattern of a single pump beam that has been split and recombined. Our design uses a robust interferometrically based method with built-in phase alignment of the signal to the pump-induced dynamic Bragg grating. In addition, because our loop can be short (less than 1 m), it does not suffer from problems typically associated with nonlinear optical loop mirrors, such as large physical size, high latency, and extreme sensitivity to environmental fluctuations. Given the EDF used in our experiment, one can tune the filter in a few milliseconds (limited by the excited-state lifetime of the erbium ions) by simply changing the wavelength of the pump light that establishes the intraloop grating. The filter may be operated with the pump and the signal entering either the same or opposite ports of the 50/50 coupler located at the loop mirror input. Switching between gain and absorption changes the filter function between notch and bandpass, depending on the input ports chosen for the pump and the signal.

The robust LMF configuration, shown in Fig. 1, is simply a 50/50 coupler with the two outputs joined by a section of saturable gain or absorber. A standing wave created by counterpropagating pump waves creates a grating in the intraloop saturable medium. In the

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saturable-gain case, the standing wave creates alternating regions with gain and without gain (where the gain is bleached). Similarly, alternating regions with and without absorption are created in the saturable-absorber case. These gratings have a period of one-half the pump wavelength. When a secondary data signal is input to the loop mirror, it too creates a set of counterpropagating waves within the saturable medium. This data signal should have lower amplitude to avoid disturbing the original pump-induced grating. The gain or absorption experienced by this signal standing wave depends on its phase and periodicity relative to the grating induced by the pump standing wave. By choosing which of the two loop input ports is used for the pump and signal waves, we can reconfigurably determine whether the interference patterns created by the two pairs of counterpropagating standing waves are exactly in phase (for the same input port) or π out of phase (for different input ports). This determination is possible because light coupled across a coupler undergoes a $\pi/2$ phase shift relative to light coupled straight through. An important feature is that the relative phases of the pump and the signal at the loop inputs are irrelevant.

The LMF operates as follows: When the pump and the signal enter the loop through the same input and have the same frequency, the signal interference pattern will be in phase with the pump interference pattern. Hence, for a saturable gain, these signals experience the regions bleached by the pump and pass without gain. As the signal frequency begins to deviate from the pump frequency, the interference pattern phase-matching condition will no longer be satisfied and these signals will be amplified, thereby creating a notch filter. The strongest amplification occurs when the interference patterns are π rad out of phase, where the signal standing wave coincides maximally with the regions where the pump has not bleached the gain. With further frequency deviation, the interference patterns become increasingly decorrelated, and amplification levels off to an intermediate value. If, however, the pump and the signal enter the loop through different ports, their interference patterns will be π rad out of phase. In this case, signals near the frequency of the pump will be amplified. As the signal frequency deviates from the pump frequency, the interference patterns will no longer be π rad out of phase, and amplification will decrease, resulting in a bandpass filter.

For a saturable absorber we have the opposite situation: When the pump and the signal enter the loop through the same port we have a bandpass filter, whereas if the pump and the signal enter through different ports we have a notch filter. Thus, simply by choosing the proper inputs for our signals, we can create saturable-gain or saturable-absorber bandpass or notch filters. Using different input ports for the pump and signal permits convenient separation at the output of the signal and the pump, which are at similar frequencies.

The coupled differential equations for the normalized counterpropagating pump wave amplitudes $A_{1\pm}(x)$ and signal wave amplitudes $A_{2\pm}(x)$ in the saturable-gain or -absorber section are known.[8] When we rewrite these equations in terms of pump and signal intensities, with $P_\pm = |A_{1\pm}|^2$ and $S_\pm = |A_{2\pm}|^2$, they become

$$\frac{dP_\pm}{dz} = \pm \frac{g_0}{(a^2 - b^2)^{1/2}} \left[P_\pm - \frac{a - (a^2 - b^2)^{1/2}}{2} \right], \quad (1)$$

$$\frac{dS_\pm}{dz} = \pm \frac{g_0}{(a^2 - b^2)^{1/2}} \Bigg[S_\pm - (1 + \Omega^2)^{1/2} |A_{2+}A_{2-}| \times \frac{a - (a^2 - b^2)^{1/2}}{b} \cos(\mp 2\Delta k z + \phi_{21} + \varphi) \Bigg], \quad (2)$$

where g_0 is the unsaturated-gain ($g_0 > 0$) or -absorption ($g_0 < 0$) coefficient, $a = 1 + \Omega^2 + P_+ + P_-$, $b = 2|A_{1+}A_{1-}|$, Ω is the detuning of the pump wave from the absorption resonance, Δk is the signal wave number offset from the pump (i.e., a measure of the phase mismatch between the pump and the signal waves), z is the distance measured from the center of the saturable medium, ϕ_{21} is the relative phase

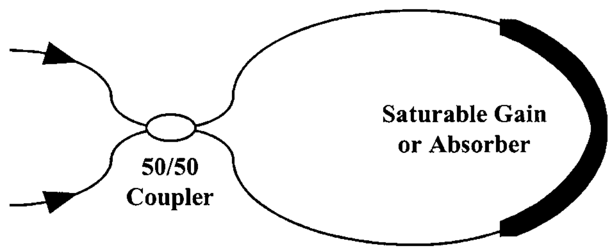

Fig. 1. The LMF is simply a fiber loop mirror containing a saturable-gain or -absorber section.

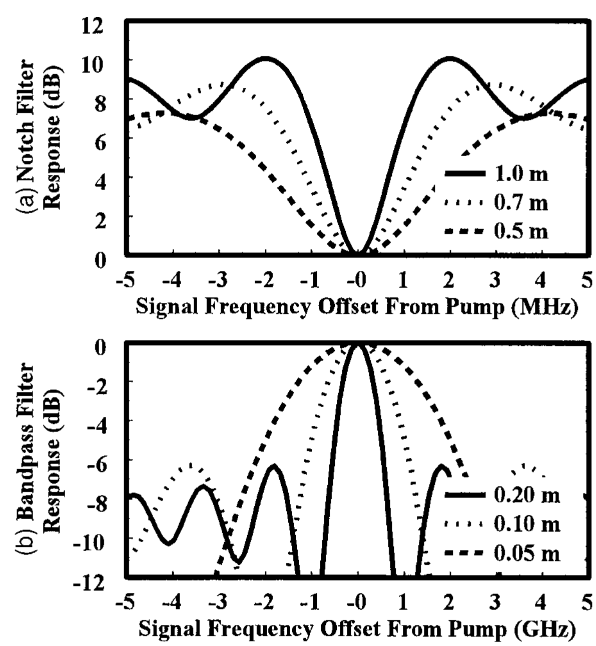

Fig. 2. Theoretical responses of (a) notch LMF's with saturable-gain gratings and (b) bandpass LMF's with saturable-absorber gratings, for several EDF lengths.

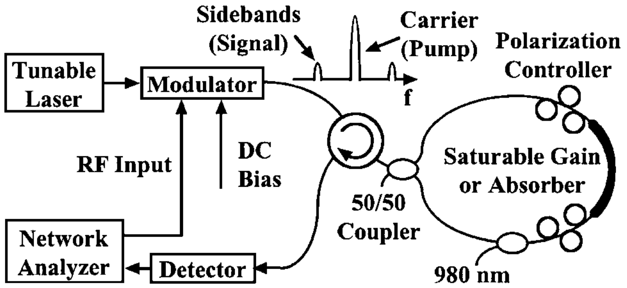

Fig. 3. Experimental LMF characterization setup for pump and signal input to the same port of a 50/50 coupler.

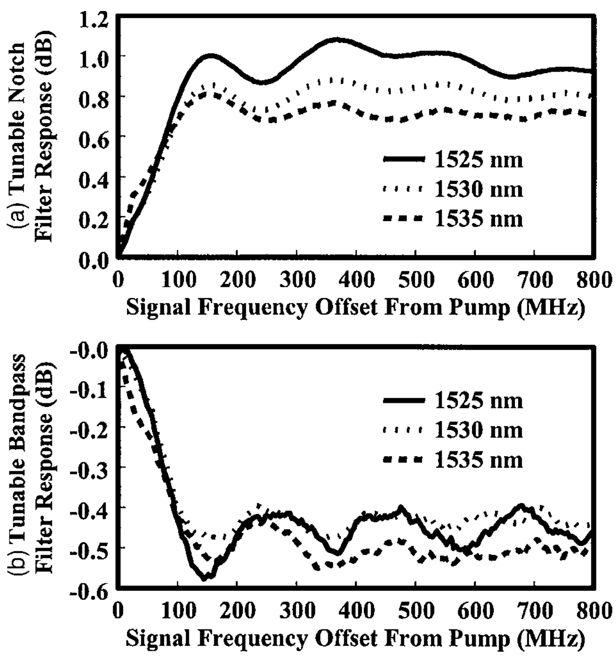

Fig. 4. Measured responses of (a) tunable notch LMF's with saturable-gain gratings and (b) tunable bandpass LMF's with saturable-absorber gratings.

between the interference patterns of the counterpropagating pump and signal waves at $z = 0$, and $\varphi = \arg[g_0(1 + i\Omega)]$.

Figure 2(a) shows narrow-bandwidth notch filter responses (as a function of signal frequency offset from the pump wave) based on saturable-gain gratings (EDF lengths, 1.0, 0.7, and 0.5 m; $P_\pm = 7.0$ dB; $g_0 = 14.5\ \mathrm{m}^{-1}$). Figure 2(b) shows wider-bandwidth bandpass filter responses based on saturable-absorber gratings (EDF lengths, 0.2, 0.1, and 0.05 m; $P_\pm = -7.0$ dB; $g_0 = -17.3, -34.5, -69.1\ \mathrm{m}^{-1}$). In each case the pump and the signal are input to the same port of the 50/50 coupler, and $\Omega = \varphi = \phi_{21} = 0$. Similar results are obtained when the pump and the signal are input to different ports of the 50/50 coupler.

The experimental setup that is used to measure LMF responses when the pump and the signal enter the same port of the 50/50 coupler is shown in Fig. 3. The parameters of the saturable medium are chosen based on the desired filter characteristics (e.g., the bandwidth is approximately proportional to the inverse of the length of the saturable medium). A network analyzer makes calibrated measurements and provides the rf drive signal to the modulator. Modulating the optical carrier shifts a fraction of the power into sidebands. As the modulator rf input frequency input is swept, these sidebands probe the filter response. The magnitude of the sidebands (signals) was adjusted to 30–40 dB below the carrier (pump) power. Note that the pump coherence length must be longer than the length of the saturable-gain or -absorber section, a requirement easily satisfied by commonly available lasers. The filter response is insensitive to the input state of polarization, but a polarization controller is used at each end of the EDF to maximize interference between the counterpropagating waves and ensure that the signal is coupled out through the proper port of the loop mirror. This setup did not allow the signal polarization to be adjusted independently of the pump polarization, but the two need not match. 980-nm light is coupled into the EDF for the saturable-gain case. A similar configuration is used for LMF characterization when the pump and the signal enter different ports of the coupler.

Figure 4(a) shows the response measured with the configuration shown in Fig. 3 for notch LMF's based on saturable-gain gratings at 1525, 1530, and 1535 nm. These filters were created by use of a 1-m EDF with a peak absorption coefficient near 1530 nm of $14.5\ \mathrm{m}^{-1}$. The power in each counterpropagating pump wave was 0 dBm. 20 dBm of power at 980 nm was coupled into the loop to provide gain. Without the 980-nm input, gain becomes absorption, and the notch filters are converted into bandpass filters, as shown in Fig. 4(b).

Experimental results match predicted filter shapes and bandwidths, but the measured filter strength is less than expected. Based on theoretical predictions, we believe that the experimental results could be improved significantly.

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