Stabilization of microwave signal generated by a dual-polarization DBR fiber laser via optical feedback

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Abstract: Microwave signals can be generated by beating the two orthogonal polarization modes from a dual-frequency fiber grating laser. In this paper, we present that the phase noise of the microwave signal can be significantly reduced via optical feedback by cascading an external cavity. This is achieved as a result of the bandwidth narrowing of each polarization laser mode when introducing phase-matched feedbacks into the laser cavity. By optimizing the external cavity length and the feedback ratio, the noise level over low frequencies has been reduced by up to 30 dB, from −42 to −72 dBc/Hz at 1 kHz, and from −72 to −102 dBc/Hz at 10 kHz. Meanwhile the relaxation resonant peaks can be eliminated. Compared with the existing techniques, the present method can offer a cost-effective, low-noise microwave signal, without the requirement for complex electrical feedback system.

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References and links


1. Introduction

The generation of optically carried microwave signals is of great interest for a wide range of applications. It allows for low-loss and broadband transmissions of RF signals over optical fiber, and enables the immunity against electromagnetic fields. A number of techniques have been proposed to generate a stable microwave signal, including external modulation of a semiconductor laser or utilizing the nonlinearity effects in lasers [1]. Microwave signals can be straightforward obtained by heterodyning two lasers with a certain frequency difference. However, beating two uncorrelated optical (laser) signals can lead to high phase noise. The phase noise level is a significant measure of signal quality which reflects the purity and bandwidth of a microwave signal. The noise can be suppressed by optical injection locking or composing phase-lock loop, which needs a high quality microwave reference and complex electronic system [2–6]. Alternatively, one can obtain microwave signals by beating the output from a dual-frequency fiber/solid-state laser [7–11]. The coherence of the signals is better as a result of the common resonant cavity. In addition, this method does not need any reference source and greatly reduces system cost. We have demonstrated the generation of microwave signals by use of a dual-polarization DBR fiber laser with a signal-to-noise ratio (SNR) over 60 dB, a temperature dependency as low as 10⁻⁵ °C, and an intrinsic tunability with a range over 15 GHz [10]. In this paper, we present the stabilization of the microwave signal by introducing an optical feedback. When phase-matched feedbacks are introduced, each polarization laser mode is stabilized, yielding a significant reduction in the phase noise level of the beat signal. By optimizing the external cavity length and the feedback ratio, the noise level is reduced by 30 dB, from −42 to −72 dBc at 1 kHz, and from −72 to −102 dBc at 10 kHz. Compared with the existing techniques in literature, the present method offers a cost-effective, high-quality optically generated microwave source.

2. Principle

Fig. 1. The schematic of a fiber laser with an external cavity to offer an optical feedback.
Figure 1 shows the schematic of the proposed microwave signal generator with optical feedback for stabilization. The DBR laser has a cavity length $L$ and reflectivities of cavity mirror $r_1$ and $r_2$, respectively. Single-longitudinal-mode output can be established with an effective cavity length $L$ of mm order in rare earth doped fibers. The laser naturally emits two polarization modes and generates a beat signal at RF region. The beat frequency can be from MHz to GHz, depending on the intrinsic birefringence of the active fibers. The frequency noise spectrum density $S_v(f)$ of the microwave signal can be expressed by [12]:

$$S_v(f) = S_{v_i}(f) + S_{v_o}(f) - 2S_{v_{oo}}(f),$$ (1)

where $S_{v_i}(f)$ and $S_{v_o}(f)$ are the functions for each polarization mode and $S_{v_{oo}}(f)$ denotes the cross-spectral density which describes the degree of correlation between the two mode. The two polarization modes share the same laser cavity, yielding a high correlation degree. As a result, the beat frequency noise level falls by approximately 9dB below that for each polarization mode [12]. The correlation $S_{v_{oo}}(f)$ is determined by the host and dopant materials and the geometry of the glass fiber which is hardly affected by optical feedback. It is almost independent on frequency offset $f$. As a result, the beat signal has a noise profile the same as each polarization mode and only a lower level. For a short cavity fiber laser with DFB or DBR schemes, the frequency noise arises from thermal fluctuations which have the equilibrium part contributed from passive components of the laser and the nonequilibrium part from the gain media. In a rare-earth doped fiber laser, the noise spectrum presents a $1/f$ profile over the low and intermediate frequencies where nonequilibrium thermal fluctuations dominate the frequency noise [12, 13].

In order to stabilize the beat signal, an external cavity with a length of $L_{ext}$ and an endface reflectivity $r_{ext}$ is cascaded to the laser cavity, as shown in Fig. 1. The photon round-trip times in the laser cavity and the external cavity can be expressed by $\tau = 2L_{ext}c$ and $\tau = 2L_{ext}n/c$, respectively. The feedback fraction $R_{ext}$ is defined as the ratio between the feedback power to the laser cavity and the emitted power. The phase of the reflected light is written as $\Phi_{ext} = 2\pi\tau_{ext}$. In the case of weak feedback ($R_{ext} \ll 1$), we can use Lanf-Kobayashi(L-K) [14] rate equation to describe the behavior of this compound-cavity laser system, which writes [15–17]:

$$\begin{bmatrix}
\Delta g = 2k \cos(\omega_0 \tau + \Phi_{ext}) \\
\Delta \omega \tau = \omega \tau - \omega_0 \tau = -C \sin(\omega \tau + \tan^{-1} a + \Phi_{ext})
\end{bmatrix},$$

(2)

where $\Delta g$ represents excess gain, and $\Delta \omega$ denotes frequency shift and $a$ is linewidth broadening factor. The feedback parameter is defined by

$$C = k\tau \sqrt{1+a^2},$$

(3)

where $k = \sqrt{R_{ext} \frac{T}{\tau_s \sqrt{r_i}}} \frac{\tau}{\tau_s \sqrt{r_i}}$ is the feedback rate. The dependence of the noise on the feedback parameter can be expressed by [15–17]:

$$S_v(f) = \frac{S_{v_{oo}}(f)}{[1+C \cos(\Phi_{ext} + \tan^{-1} a)]^2},$$

(4)
where $S_f(f)$ and $S_{f'}(f)$ are the laser frequency noise spectrums before and after introducing an optical feedback, which indicates that the noise can be effectively lowered when the phase-matching condition $\Phi_{\text{ext}} = 2n\pi - \tan^{-1} a$ is satisfied. At phase matching the mode hopping can be suppressed and it turns out that the emission frequency will lock to the solution with lowest phase noise. The amplitude of $S_{f''}(f)$ changes at the same rate with each polarization mode since the correlation degree remains unchanged. As a result, the beat-signal noise falls with the same rate as each polarization mode. Higher feedback parameter $C$ can result in lower noise level and narrower bandwidth for the beat signal. Equation (3) indicates that the amplitude of $C$ can be increased by using longer delay fiber for more external cavity round trip time $\tau$ or by increasing the feedback fraction $R_{\text{ext}}$. However, longer external cavity can induce more possible modes and makes the laser susceptible to mode hopping, especially when the external cavity mode separation gets close to the relaxation resonant frequency of the fiber laser. The resonant frequency is about 500 kHz, corresponding to an external cavity length of 200m. In the experiment, the external cavity length should be kept below this value to avoid severe mode hopping.

3. Experiment and discussion

![Experimental setup of the proposed microwave source with optical feedback](image)

Figure 2 shows the experimental setup of the microwave source with optical feedback. In the experiment, the distributed Bragg reflector (DBR) fiber laser is fabricated by photo-inscribing two wavelength-matched Bragg grating with lengths of 6 mm and 5 mm with coupling strengths of 30 dB and 27 dB, respectively. The effective cavity length is as short as about 5mm to ensure single-longitudinal-mode output. The lasing wavelength is about 1553 nm, determined by the pitch of the phase mask. A 980 nm laser diode is employed to pump the laser via a wavelength-division multiplexer (WDM). An in-line polarizer is used to maximize the intensity of the beat signal. The external optical feedback is provided by use of a C-band reflective mirror. The delayed time is controlled by varying the length of the external cavity. A variable optical attenuator (VOA) is used to change the feedback rate $R_{\text{ext}}$. The polarization state of the feedback is controlled by use of a polarization controller. An optical isolator is used to prevent unwanted optical feedbacks from the output end. The beat signal is monitored by use of an electronic spectrum analyzer (Anritsu, MS-2692A).

Figure 3(a) shows the measured phase noise spectrum when varying the feedback rate with a fixed external cavity length. The measured mode separation $1/\tau = 2.331\text{MHz}$, corresponding to $L_{\text{ext}} = 45$ m. The feedback fraction $R_{\text{ext}}$ varies from −30.6 dB to −3 dB by
adjusting the VOA, corresponding to the amplitude of \( C \) from 3 to 40. By carefully adjusting the polarization controller, phase matching can be satisfied and the maximum linewidth reduction can be achieved at a certain feedback rate. We found that the phase noise spectrum keeps the 1/f profile and can be lowered by 16 dB when the feedback rate increases to −3 dB.

Figure 3(b) shows the measured phase noise spectrums for different external cavity lengths with a fixed feedback fraction \( R_{\text{ext}} = -8.6 \text{dB} \). The mode separations 3.7815, 2.331 and 0.8485 MHz, corresponding to external cavity lengths of 27, 45, and 122 meters, result in noise levels −86, −90, and −97 dBc at 10 kHz, respectively. The amplitude of \( C \) increases with longer external cavity, yielding a reduction of phase noise. When \( C \) gets close to 30, the noise reduction seems begin to saturate. We found that the saturation of phase-noise reduction intends to happen at high frequency region, rather than in lower frequency region. The maximum noise reduction that can be achieved in our experiment is about 30 dB over frequencies lower than 10 kHz and about 25 dB over higher than 30 kHz, with \( L_{\text{ext}} = 130 \text{ m} \) and \( R_{\text{ext}} = -3 \text{dB} \) (represented by the pink curve in Fig. 3(c)). The corresponding phase noise levels are −72dBc at 1kHz and −102dBc at 10kHz, respectively.

Figures 3(c) and 3(d) exhibit the calculated and measured noise reduction ratios as a function of feedback ratio and external mode separation, respectively. The measured result is expressed in the form of phase noise spectrum \( L_{\phi}(f) \) in the figures, which is directly linked to frequency noise spectrums \( S_{\phi}(f) \) by [22]:

\[
L_{\phi}(f) = S_{\phi}(f) + 20 \log \frac{f}{1(\text{Hz})} + 3\text{dB} \tag{5}
\]

The calculation is carried out based on Eq. (4) under the assumption of in-phase condition. In the calculation, we set \( T = -30\text{dB} \), \( r_1 = r_2 = 1 \), and \( 1/\tau_0 = 20 \text{ GHz} \). The linewidth broadening factor, is set as \( a = 2.1 \), for better fit to the experimental result [19, 20]. This value is a higher than that calculated by Foster [20,21](about 0.5), but within the range measured by E. Rønnekleiv [19] (from 2.1 to 3.8). The calculated and measured results are in good accordance, indicating that the L-K model can well describe the behavior of the Er-doped fiber laser with optical feedback.

When further increasing the amplitude of \( C \), the introduced feedback cannot be considered as a weak perturbation and the L-K equations are not applicable. In this case, the laser linewidth will greatly broaden, corresponding to the so-called “coherence collapse regime”. This behavior is similar to the semiconductor lasers with optical feedbacks, as described in [14–16].The present fiber grating laser is different from the semiconductor lasers in the following aspects: First, the Er-doped fiber has a relatively low gain (the peak absorption 18.4 dB/m in our experiment), and a longer cavity length and a high-Q resonant cavity (with high \( r_1 \) and \( r_2 \)) are needed to reach lasing oscillation. Second, the linewidth enhancement factor of Er-doped fiber is much lower than the counterparts of the semiconductor lasers [19, 20]. Based on the definition of feedback rate parameter, we can see that the effect of optical feedback on laser is proportional to laser cavity round-trip time, Q factor of the cavity, and the linewidth enhancement factor. That means a fiber grating laser needs a much longer external cavity or much higher feedback fraction than the semiconductor lasers to reach a certain value of \( C \). In addition, it is difficult for DBR fiber laser to reach strong feedback (corresponding to regimes 4 and 5 for semiconductor lasers) to observe the coherence collapse.
Fig. 3. Measured phase noise spectrums with (a) a fixed external cavity length of $L_{\text{ext}} = 45$ m and varying feedback rates, and (c) a fixed feedback fraction of $R_{\text{ext}} = -8.6$ dB and different external cavity length (different external mode separations). Calculated and measured noise reduction ratio as a function of feedback ratio (b) and external mode separation (d).

Figure 4 shows the measured spectrums of the microwave signal with and without a 3-dB feedback and an external cavity mode separation of 0.8335 MHz (corresponding to the pink curve in Fig. 3(b)). It can be seen that the relaxation resonant peaks have been completely eliminated. The noise level has also been reduced by more than 10 dB, which may reach the noise floor of the photodetector [17, 18]. Note that the external perturbations, including thermal fluctuation and vibration arising from the experimental facilities, can induce phase drifting and cause phase mismatch. We found that the in-phase status can only maintain for a few minutes without specific isolation. In addition, acoustic noise can possibly cause mode hopping when a long external cavity is used. Therefore, careful isolation from environmental perturbations is favorable in practical use to avoid these environmental perturbations.

Fig. 4. Measured spectrums of the microwave signal with and without the optical feedback $R_{\text{ext}} = 3$ dB and $L_{\text{ext}} = 122$ m.
Table 1 compares the experimental result with the existing techniques in literature towards the fabrication of a stable optically generated microwave signal. The conventional methods, including external modulation and nonlinear effect have been applied for semiconductor lasers, with quite high phase noises [6]. Microwave signals generated by beating two separate, uncorrelated lasers can be stabilized by optical injection locking, by use of an optical phase-lock loop, to reach a noise level close to directly beating the two polarization modes from a single fiber laser [2–5]. The microwave signals generated by a dual-frequency fiber laser, can also be stabilized by phase locking, and the phase noise can reach −80 dBc at 1kHz and −105 dBc at 10kHz [9]. However, all these phase locking techniques need a high quality microwave reference source or complex electronic equipment. In this work, we present the stabilization of the beat signal by use of optical feedback and achieve −72 dBc at 1kHz and −102 dBc at 10kHz. In comparison, the method is straightforward, cost effective and can enable a low phase noise output.

Table 1. Performance comparison of various optical techniques to generate a stable microwave signal.

<table>
<thead>
<tr>
<th>Method</th>
<th>Phase noise(dBc/Hz)</th>
<th>Method</th>
<th>Phase noise(dBc/Hz)</th>
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<tbody>
<tr>
<td>Nonlinear effect [6]</td>
<td>−75 dBc@5kHz</td>
<td>Er dual-polarization lasers [11]</td>
<td>−40 dBc@1kHz</td>
</tr>
<tr>
<td>Optically locked DFB semiconductor lasers [2]</td>
<td>−73 dBc@10kHz</td>
<td>Er-Yb dual-polarization lasers [8, 9]</td>
<td>−30 dBc@1kHz</td>
</tr>
<tr>
<td>Locking master/slave lasers [4]</td>
<td>−100 dBc@100kHz</td>
<td>Phase locked dual-polarization Er-Yb lasers [9]</td>
<td>−60 dBc@10kHz.</td>
</tr>
<tr>
<td>Optical injection locked Nd:YAG lasers [3]</td>
<td>−90 dBc@10kHz</td>
<td>This work</td>
<td>−80 dBc@1kHz</td>
</tr>
<tr>
<td>Phase locked dual-mode semiconductor lasers [5]</td>
<td>−77 dBc@10kHz −85 dBc@100kHz</td>
<td></td>
<td>−105 dBc@10kHz</td>
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</table>

4. Conclusion

In conclusion, we have presented the phase noise reduction of the microwave signal generated by a dual-polarization fiber grating laser by introducing an optical feedback. With phase-matched feedbacks, the linewidth of each polarization laser mode is narrowed and thus the beat signal is stabilized. By optimizing the external cavity length and the feedback ratio, the noise level over low frequencies has been reduced by up to 30 dB, from −42 to −72 dBc/Hz at 1 kHz, and from −72 to −102 dBc/Hz at 10 kHz. The relaxation resonant peaks have been eliminated. Compared with the existing techniques, the present method offers a cost-effective, low-noise microwave signal, without the requirement for complex electrical feedback system.

Acknowledgments

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