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Shupei Mo
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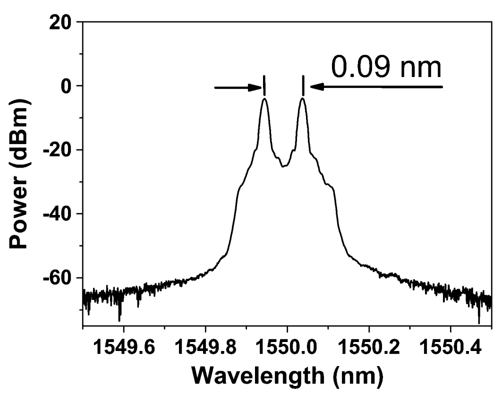
Shanhui Xu
Weinan Zhang
Dongdan Chen
Tong Yang
Wei Fan
Can Li
Changsheng Yang
Zhongmin Yang



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Microwave Signal Generation From a Dual-Wavelength Single-Frequency Highly Er^{3+}/Yb^{3+} Co-Doped Phosphate Fiber Laser

Shupei Mo,[1] Zhouming Feng,[1] Shanhui Xu,[1] Weinan Zhang,[1] Dongdan Chen,[1] Tong Yang,[1] Wei Fan,[1] Can Li,[1] Changsheng Yang,[1] and Zhongmin Yang[1,2]

[1]State Key Laboratory of Luminescent Materials and Devices and Institute of Optical Communication Materials, South China University of Technology, Guangzhou 510640, China
[2]Special Glass Fiber and Device Engineering Technology Research and Development Center of Guangdong Province, Guangzhou 510640, China

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Abstract: Narrow linewidth microwave signals generated from a heterodyne detection configuration of a dual-wavelength (DW) single-frequency highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser is presented. The oscillating cavity of the fiber laser consists of a dual-channel narrow-band fiber-Bragg-grating (DC-NB-FBG), a 0.7-cm-long Er^{3+}/Yb^{3+} co-doped phosphate fiber and a wideband FBG (WB-FBG). The wavelength selecting gratings are spatially separated to create partially separated resonant cavities. Highly Er^{3+}/Yb^{3+} co-doped phosphate fiber ensures that the mode competition is relatively weak under low pump power. DW single-frequency lasing with laser linewidths of <3 kHz is achieved. A 12.014-GHz microwave signal with a 3-dB linewidth of <3 kHz is obtained from the heterodyne detection of the DW fiber laser.

Index Terms: Fiber lasers, microwave photonics.

1. Introduction

Unlike traditional schemes of generating microwave signals with electric circuits and transmitting through coaxial cables, photonic generation of microwave signals offers a simple way of generating optical carrier signals and transmitting it via low-loss, inexpensive optical fibers over large distances. Photonic generation of microwave or millimeter wave signals have attracted great attention due to its potential applications in satellite communication, radio-over-fiber network (RoF), radar, instrumentation, and warfare systems [1]–[3]. There are many photonic techniques to generate microwave signals; for example, microwave signal generation based on external modulation [4], [5], optical heterodyne detection of two phase locked lasers [6], the direct photodetection of the output from a mode-locked laser [7], the dual-wavelength single-longitudinal-mode (DW-SLM) laser sources [8]–[18]. The former three techniques require external microwave sources to operate or specially designed radio frequency (RF) and/or optical filters to ensure a clean RF spectrum, which increase the complexity and cost of the system. On the other hand, the microwave signal generation from a DW-SLM laser source facilitates a low-cost and simple system in the sense that there are no external microwave sources or RF filters needed in the system.

DW-SLM lasers using a fiber ring structure or other long linear cavity structures were demonstrated [8]–[11]. Implementations were utilized in the aforementioned lasers to obtain stable SLM operation, such as saturable absorbers [8] or other complex structures [9]–[11], but the integration of the laser turns out to be even harder. Moreover, mode competition inside DW-SLM lasers tends to destabilize the system. By introducing divergence into the laser cavities, e.g., to utilize polarization maintaining (PM) components [12], [13] or to make use of partially separated cavity structures [14]–[17], one can obtain a more stable system. Lasers utilizing PM-fiber-Bragg-gratings or PM gain fibers are believed to be more stable for the divergence induced by polarization hole burning effect [12], [13]. However, the spacing of the laser wavelengths was determined by the birefringence of the PM fiber or gain fiber, making it hard to achieve tunable or switchable microwave-signal output.

Partially separated cavity structures were realized by both distributed feedback (DW-DFB) lasers and distributed Bragg reflector (DW-DBR) lasers [14]–[18]. Recently, photonic generation of microwave signals from short cavity DW distributed feedback (DW-DFB) lasers utilizing spatially separated sub-fiber-Bragg-gratings has been demonstrated with considerable stability [14]–[16]. However, the manufacture of π-phase-shifted sub-FBGs could be more complicated. Moreover, the gain medium and π-phase-shifted sub-FBGs are physically collocated, which can result in problems such as the instabilities associated with grating wavelength drifts and the reduction in active ion lifetime after UV exposure [16].

Short-cavity DW distributed-Bragg-reflector (DW-DBR) lasers would be a more favorable choice if the cavity structure and gain media were chosen carefully to weaken the mode competition [17], [18]. R. K. Price *et al.* reported a tunable DW semiconductor laser source consisting of two surface-etched DBR lasers with outputs combined by a y-branch coupler [17]. However, semiconductor devices typically had a laser linewidth of a few megahertz, which results in microwave signals that are inadequate for use in microwave systems where high-purity, very-narrow-line-shape signals are required [2]. Therefore, a compact and cost-effective photonic microwave sources with special laser cavity struture and gain media would be propitious for various applications.

In this paper, we report the experimental demonstration of photonic generation of microwave signals from a dual-wavelenthg single-frequency highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser. The wavelength selecting sub-gratings are spatially separated to create partially separated resonant cavities for each of the longitudinal modes. Highly Er^{3+}/Yb^{3+} co-doped phosphate fiber ensures that mode competition is relatively weak under low pump power. The system is very compact in comparison to other fiber-base photonic microwave sources. A 12.014-GHz microwave signal with a linewidth of $<$ 3 kHz is generated from the heterodyne detection of the free running DW fiber laser.

2. Experimental Setup and Principles of Operation

Fig. 1 shows the configuration of the microwave signal generation based on the DW single-frequency highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser. The laser cavity is established by a dual-channel narrow-band fiber-Bragg-grating (DC-NB-FBG) (4.0 cm) and a wideband FBG (WB-FBG) (2.5 cm) that are fusion spliced to the end facets of a 0.7 cm-long homemade high gain Er^{3+}/Yb^{3+} co-doped phosphate fiber. The DC-NB-FBG is fabricated by fusion splicing two narrow-band FBGs (NB-FBG) with a reflection band separation of approximately 0.1 nm. The reflectivity of the DC-NB-FBG is 50%, and the 3-dB bandwidth of each channel is 0.08 nm with a channel separation of approximately 0.1 nm. The DC-NB-FBG functions as a mode-selecting element similar to the NB-FBG in the single-frequency fiber laser cavities demonstrated in [19] and [20]. The spatially separated sub-NB-FBGs create partially separated resonant cavities for each of the longitudinal mode. The WB-FBG has a 3-dB bandwidth of 0.4 nm and a reflectivity of $>$ 99.95%. Detailed description about the fabrication and other characteristics of the phosphate fiber can be found in [19].

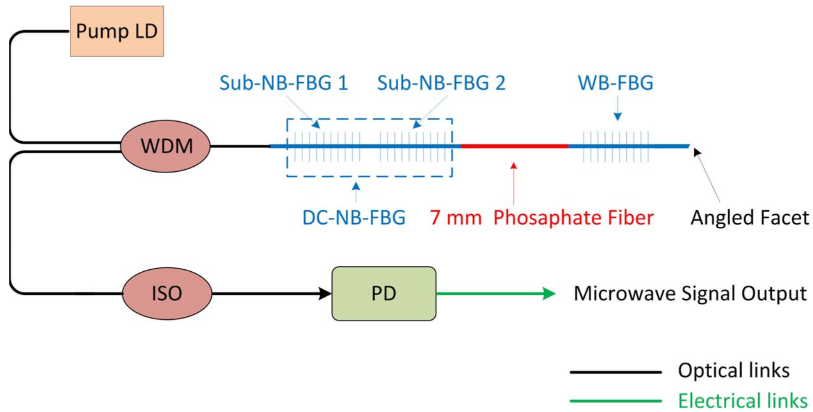

Fig. 1. Experimental setup of microwave signal generation from the DW single-frequency highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser.

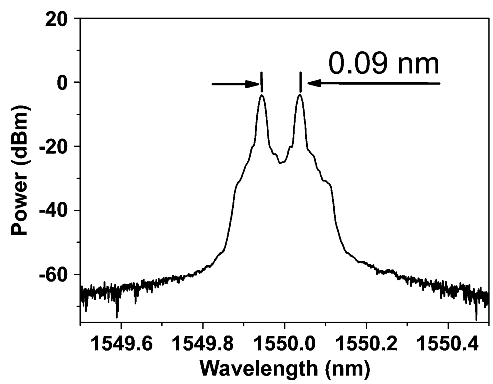

Fig. 2. Laser spectrum of the DW fiber laser.

The DW fiber laser was pumped by a commercially available single mode 980-nm laser diode (LD) through a 980/1550-nm wavelength division multiplexer (WDM). The WDM output was passed through an isolator (ISO) to prevent back reflections, which destabilized the fiber laser. The DC-NB-FBG, together with the high-reflection WB-FBG, selects the lasing wavelengths. The optical tones with different wavelengths beat at the photodetector (PD), and generated an electric beat note at the output of the PD. The short cavity and the DC-NB-FBG ensure that only one longitudinal mode is supported by each channel. By thermally stabilizing the laser cavity, simultaneous DW lasing could be stably achieved, producing a clean spectrum of the microwave heterodyne signal generated from the DW fiber laser. Since the centered frequency of the heterodyne signal was determined by the frequency difference of the two optical tones, tuning of the heterodyne microwave signal was feasible by thermally tuning the two sub-FBGs.

3. Results and Discussions

The output spectrum of the fiber laser was recorded using an optical spectrum analyzer (OSA), as shown in Fig. 2. DW lasing with an output power of 2 mW was achieved at a pump power of 56 mW. Two optical tones with center wavelengths of 1549.946 nm and 1550.037 nm were recorded. The power difference of the laser wavelengths was less than 0.14 dB. The laser output was passed to a 12-GHz PD and an electrical spectrum analyzer (ESA). The electrical spectrum of the microwave heterodyne signal was shown in Fig. 3. The measurements were taken at a 1-min interval over 10 min. A microwave signal centered at 12.014 GHz was recorded with a resolution bandwidth (RBW) of

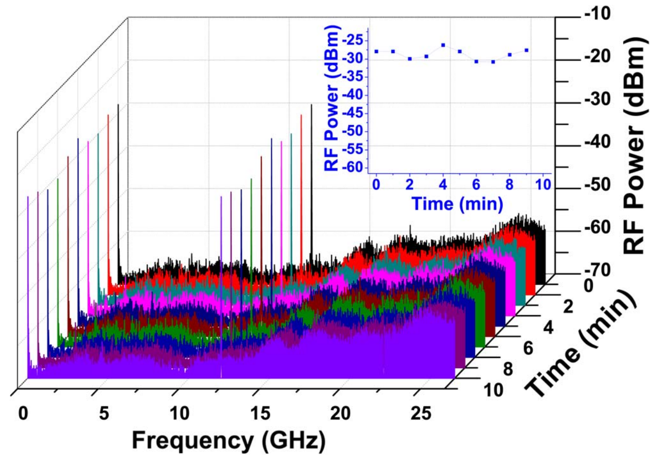

Fig. 3. Electrical spectrums of the microwave beat signal centered at 12.014 GHz taken at 1-min interval over 10 min. (Inset) Power variance of the beat signal.

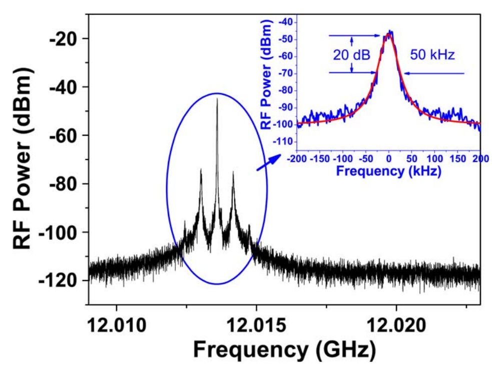

Fig. 4. Electrical spectrum of the signal with an expanded frequency scale. (Inset) Magnified picture of the same signal. (Red line) Lorentz fitting of the microwave signal.

10 MHz and a sweep time of 77.82 ms. The power variance was plotted on the inset in Fig. 3. We recorded a power variance of $<$ 3 dB over 10 min, which was mainly contributed by external perturbations, e.g., acoustic noises and temperature changes. By improving the thermal stability and vibration-isolation of the DW fiber laser, we believe the stability of the microwave signal output could be improved. Despite the microwave signal generated from the heterodyning of the two optical tones, there were no other beat signals detected by the PD, which proved that each optical tone corresponded to one longitudinal mode.

To study the 12-GHz microwave signal in detail, the RF spectrum of the signal with an expanded frequency scale was recorded and shown in Fig. 4. The center frequency of the microwave signal was confirmed to be 12.0135938 GHz with an RBW of 1 kHz. The linewidth of the microwave signal was measured to be 2.5 kHz.

In Fig. 4, the two sidebands on either side of the 12-GHz peak signal were produced by the relaxation oscillations of the two optical tones with different relaxation oscillation frequencies. It was because of the different effective cavity lengths that the two longitudinal modes traveled through. The two relaxation oscillation frequency were used to calculate the Lamb's coupling constant C, which indicates whether there exists weak $(C = 0)$ or strong $(C = 1)$ mode competition between the two optical tones [21]. The calculated value of $C = 0.37$ indicated a rather weak mode competition. It was sure that there existed a certain degree of cross-gain saturation within the phosphate gain fiber, but the high doping-concentration of the gain fiber assures that under a relatively low pump

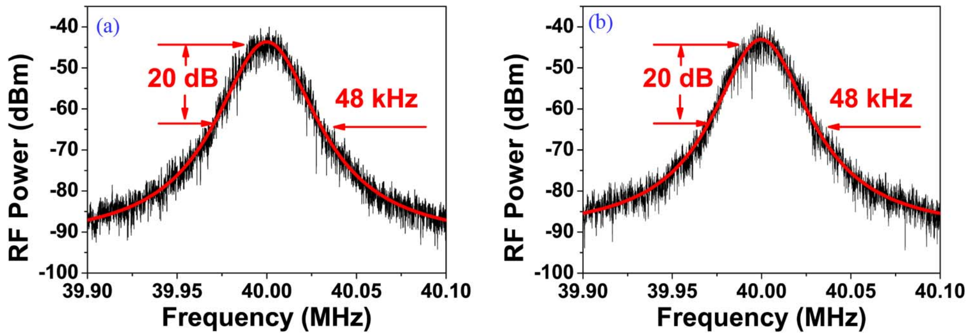

Fig. 5. (a) and (b) Lineshape of the heterodyne signals of the laser emitting at shorter and longer wavelengths. (Red lines) the Lorentz fit of the heterodyne lineshapes.

power (just above laser threshold), the cross-gain saturation did not deprave the mode competition. Moreover, spatial hole burning limits the amount of cross-gain saturation and thereby allows simultaneous DW lasing [22].

To further verify the linewidth characteristic of the microwave signal, the linewidth of both lasing signals was measured. We used a narrow-band FBG filter with a 3-dB bandwidth of 0.06 nm and a circulator to extract each laser signal. Each laser linewidth was estimated by a self-heterodyne method with a 48.8-km fiber delay and a 40-MHz fibered acousto-optical modulator (AOM). The self-heterodyne signals were recorded using an ESA with an RBW of 100 Hz. The linewidth of each laser signal was measured, as shown in Fig. 5. A laser linewidth of 2.4 kHz FWHM at the shorter wavelength and a linewidth of 2.8 kHz FWHM at the longer wavelength was estimated, as shown in Fig. 5(a) and (b). Thus, we can conclude that the linewidth of the heterodyne microwave signal was less than 3 kHz.

4. Conclusion

In summary, a 12.014-GHz microwave signal with a linewidth of 2.5 kHz generated from a DW single-frequency highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser is presented. The Lamb's coupling constant of the fiber laser was calculated to be 0.37, indicating weak mode competition. The power variance of the microwave beat signal over 10 min was measured to be < 3 dB. By using partially separated cavity structure and highly Er^{3+}/Yb^{3+} co-doped phosphate gain fibers, we were able to avoid strong mode competition between the two lasing wavelengths. The system is suitable for applications in RoF and satellite communication, wherein size and capability of being integrated are of crucial importance.

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