High-power, stable dual-wavelength tunable Er:Yb fiber laser using volume Bragg gratings

2014 Appl. Phys. Express 7 032702

(http://iopscience.iop.org/1882-0786/7/3/032702)

Applied Physics Express **7**, 032702 (2014)
http://dx.doi.org/10.7567/APEX.7.032702

High-power, stable dual-wavelength tunable Er:Yb fiber laser using volume Bragg gratings

Jun Liu[1,3], Deyuan Shen[2*], Haitao Huang[3], Ting Zhao[2], Xiaoqi Zhang[1], and Dianyuan Fan[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[2]*School of Information Science and Engineering, Department of Optical Science and Engineering, Fudan University, Shanghai 200433, China*
[3]*School of Physics and Electronic Engineering, Jiangsu Normal University, Xuzhou 221116, China*
E-mail: shendy@fudan.edu.cn

Received January 7, 2014; accepted February 13, 2014; published online March 4, 2014

We report high-power, dual-wavelength tunable operation of an Er:Yb co-doped fiber laser using two volume Bragg gratings arranged in parallel. The wavelength separation for the two operating wavelengths was continuously tuned from 0.3 to 29.2 nm (0.04 to 3.7 THz) with a total output power of >13 W for a wavelength splitting range of <20 nm. A maximum output power of 17.9 W was obtained at a wavelength separation of 0.3 nm for a launched pump power of 65.3 W, which corresponds to a slope efficiency of 28.6% with respect to the launched pump power.

Laser emission in the 1.5–1.6 µm wavelength range has attracted considerable attention for many scientific and engineering applications because of their relative eye safety, good atmospheric transmission, and low loss in silica fibers. In addition, this wavelength range also facilitates the use of commercially available, low-cost, reliable telecom components such as isolators, couplers, tunable sources, fast modulators, and high-speed detectors. In particular, for many special applications involving wavelength division multiplexing optical fiber communications, fiber sensors, remote sensing, and optical beat sources for terahertz generation,[1–3] multiwavelength fiber-based sources operating in this wavelength band are very useful and have been extensively investigated. Multiwavelength (or dual-wavelength) laser oscillations in this wavelength region, which is typically realized in Er-doped or Er:Yb co-doped fiber laser (EDFL or EYDFL) systems, have been achieved by using various techniques for wavelength selection and stabilization, such as employing cascaded fiber Bragg grating (FBG) cavities[4] or a sampled FBG in a ring cavity,[5] a few-mode or multimode FBG together with polarization control acting as a filter,[6–8] FBGs written in birefringence fibers,[9–12] and many other novel methods.[13–16] FBGs are generally ideal wavelength-selection components for fiber lasers owing to their narrow linewidth, high reflectivity, and above all, good compatibility with other fiber elements. However, FBGs are ineffective for wavelength selection in large-mode-area fibers. In addition, the operating wavelength tuning range is also limited because FBGs are difficult to tune over a wide range using either thermal or mechanical stress. Therefore, all the previously reported multiwavelength fiber laser sources based on FBGs were limited to a low output power level and suffered from poor tunability. Another issue for FBG-tuned multiwavelength laser configurations is their comparatively poor stability and repeatability.[17] The reason is that it is difficult to revert to the FBG's original position to produce the previous wavelength once it has been adjusted to lock at a new wavelength. These problems can be mitigated by the use of another widely used wavelength-selection component, volume Bragg gratings (VBGs). VBGs recorded in a bulk photo-thermo-refractive glass, have attracted great attention as an effective external wavelength-selection and spectral-narrowing component owing to their excellent performance, including a high diffraction efficiency, narrow spectral selectivity, low insertion loss, and high damage threshold. We recently demonstrated widely tunable simultaneous dual-wavelength operation of a cladding-pumped high-power Tm:fiber laser based on a simple resonator containing a pair of parallel-aligned VBGs[18] in the 2 µm spectral region. In the experiment, separate feedback paths for each wavelength were established by the respective VBGs or their corresponding terminating high-reflection (HR) plane mirror, and the 3.6% Fresnel reflection from a perpendicularly cleaved fiber end facet.

In this paper, considering the great significance for applications in the 1.5–1.6 µm wavelength band, a similar laser resonator based on the novel use of a pair of VBGs in a parallel configuration was employed in the EYDFL system. The double-reflection regime from the respective VBGs in the parallel arrangement allowed stable dual-wavelength operation with a relative power fluctuation of less than ~0.8 dB for the two lines and a wavelength shift within 20 pm. In addition, each wavelength can be independently tuned by adjusting the angles of the corresponding VBG. The wavelength spacing for the two operating wavelengths was continuously tuned from 0.3 to 29.2 nm (0.04 to 3.7 THz) with a total output power of >13 W, for a wavelength splitting separation of <20 nm. An output power of up to 17.9 W with a beam propagation factor (M^2) of ~2.5 was obtained at a wavelength separation of 0.3 nm for a launched pump power of 65.3 W, which corresponds to a slope efficiency of 28.6% with respect to the launched pump power. To achieve multiwavelength operation of the EYDFL system, a third VBG was added to the external cavity to yield an output power of 18.5 W with equal lasing at 1542, 1545, and 1552 nm simultaneously.

Figure 1 shows a schematic diagram of the dual-wavelength tunable EYDFL based on the novel use of a pair of VBGs pair. The pump light was provided by a commercially available laser diode (LD; LIMO) with a maximum output power of 650 W at 976 nm. The gain fiber (Nufern) employed in this experiment had an Er:Yb co-doped phosphosilicate core with a diameter of 30 µm and a numerical aperture (NA) of ~0.2, surrounded by a 400 µm diameter pure silica D-shaped inner cladding with an NA of ~0.49. The nominal peak pump absorption at 976 nm in the Er:Yb fiber was about ~5 dB/m for the cladding-pumped regime. However, the measured effective pump absorption coefficient was somewhat lower because of the broad (~5 nm), power-dependent output spectrum of the LD pump source. The operating peak wavelength of the LD pump source was located at ~967 nm with an output power of less than 300 W. Thus, a fiber length

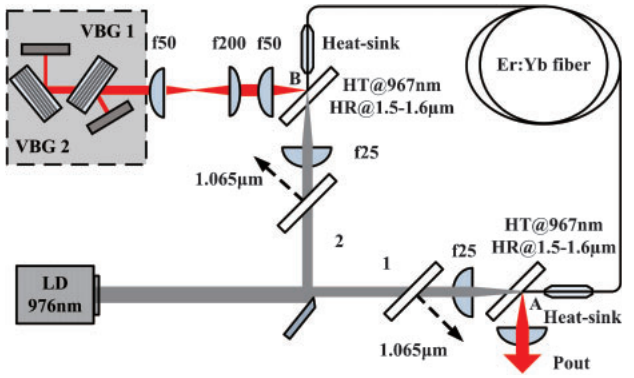

Fig. 1. Experimental schematic of tunable dual-wavelength EYDFL; components in dashed box represent dual-wavelength tuning section.

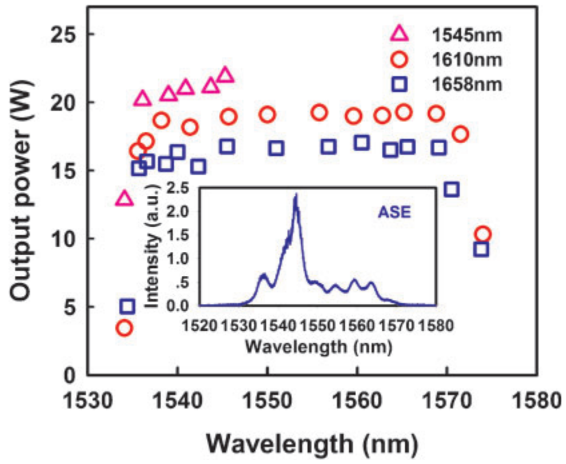

Fig. 2. Laser output power versus operating wavelength tuned by three VBGs with center wavelengths of 1545, 1610, and 1658 nm, respectively, for launched pump power of 65.3 W. Inset: ASE output spectrum of Er:Yb co-doped fiber before the system started lasing.

of ~5 m was chosen to guarantee sufficient pump absorption. The two split pump beams from the pump source, of roughly equal power, were launched into opposite ends of the gain fiber through two dichroic mirrors with the aid of two antireflection-coated plano-convex lenses 25 mm in focal length. The pump launch efficiency into the inner cladding of the gain fiber was estimated to be ~80% relative to the power incident onto the fiber. Both end sections of the fiber were carefully embedded in water-cooled V-groove heat sinks to prevent possible thermal damage to the fiber coating. The rest of the fiber was coiled into a fan-cooled Al heat sink 20 cm in diameter. Dichroic mirrors with high transmission at the pump wavelength and high reflectivity over the 1.5–1.6 μm band were positioned at an angle of 45° between the fiber ends and the pump focusing lenses to separate the laser emission from the pump light, allowing efficient extraction of the laser output.

The laser oscillation cavity for the dual-wavelength tunable EYDFL was provided by the 3.6% Fresnel reflection from a perpendicularly cleaved fiber end facet (A) and, at the opposite end (B), by a simple external cavity comprising a combination of three antireflection-coated lenses with focal lengths of 50, 200, and 50 mm, respectively, and the dual-wavelength tuning section included in the dashed box in Fig. 1. The dual-wavelength tuning section consisted of a pair of VBGs (designated as VBG1 and VBG2) aligned in parallel and their corresponding HR plane mirrors over the 1500–1700 nm band. Separate lasing feedback for each wavelength was terminated by the individual HR plane mirrors to form a complete resonator, and the VBGs were tilted for independent wavelength tuning. The corresponding focal lengths of these lenses in the external cavity were selected to make full use of the clear aperture of the VBGs. The fiber end adjacent to the external cavity (B) was angle polished at ~8° to suppress broadband feedback from the uncoated fiber facets and ~1 μm laser emission due to parasitic lasing on the Yb^{3+} transition. Another two dichroic mirrors with high reflectivity at ~1 μm and high transmission at the pump wavelength were inserted into the two pump arms to prevent the ~1 μm radiation, if any, from being fed back to the diode pump source. The laser output spectrum was recorded using an optical spectrum analyzer (Yokogawa AQ6370C).

Three VBGs (Optigrate) with different specifications were first employed to evaluate the single-wavelength tuning characteristics of the Er:Yb co-doped fiber. Among them, the two VBGs with center wavelengths of 1545 and 1610 nm both had a thickness of 7 mm and clear aperture of 6 × 8 mm^2. The other VBG, with a thickness of 9 mm and clear aperture of 5 × 5 mm^2, was designed to have a center wavelength of 1658 nm with a peak reflectivity of 99.9%. The spectral selectivity (full width at half-maximum, FWHM) of these VBGs was 0.38 nm at their respective center wavelengths. They were all wrapped in a layer of indium foil (0.1 mm in thickness) and then mounted in a copper heat sink to ensure good heat dissipation. The incident angle θ (internal) of the laser beam onto the VBG determines its Bragg wavelength λ_B as $\lambda_B = \lambda_0 \cos\theta$, where λ_0 is the wavelength at normal incidence. The angular selectivity of a VBG (half-width of first zero) is determined by $\Delta\theta = \lambda_B / 2n \sin\theta L$, where n and L are the refractive index and effective thickness of the VBG, respectively. Therefore, the operating wavelength could be tuned by adjusting the angles of both the VBG and the HR mirror. The output powers as a function of the tuned wavelength for the three VBGs are shown in Fig. 2. The configurations using a VBG with a longer center wavelength yielded lower output powers. This is attributed to the decrease in the angular selectivity $\Delta\theta$, and thus the effective reflectivity, of VBGs with longer center wavelengths. When $\Delta\theta$ is comparable with or smaller than the Gaussian angular deviation of the collimated beam onto the VBGs, part of the laser beam cannot be Bragg matched and will not be reflected. The simulated effective reflectivity at different Bragg wavelengths for the three VBGs is shown in Fig. 3. However, the experimental reflectivity should be smaller than the theoretical value because a perfect Gaussian laser beam was approximated in our simulation for simplicity. A maximum output power of 21.9 W at 1545.3 nm was generated at a launched pump power of 65.3 W for the VBG with a center wavelength of 1545 nm, despite the limited wavelength tuning range resulting from the VBG design. A wavelength tuning range of 40 nm, from 1534 to 1574 nm, was obtained for the other two VBGs with longer center wavelengths, corresponding to the wavelength spanning range of the measured amplified spontaneous emission (ASE) spectrum with a primary peak of ~1545 nm before

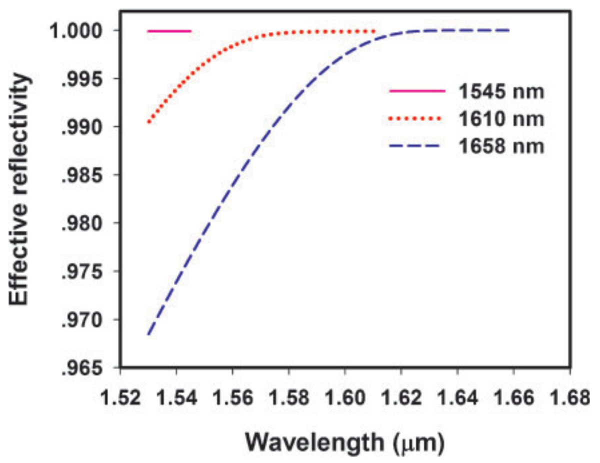

Fig. 3. Effective reflectivity at different Bragg wavelengths for the three VBGs.

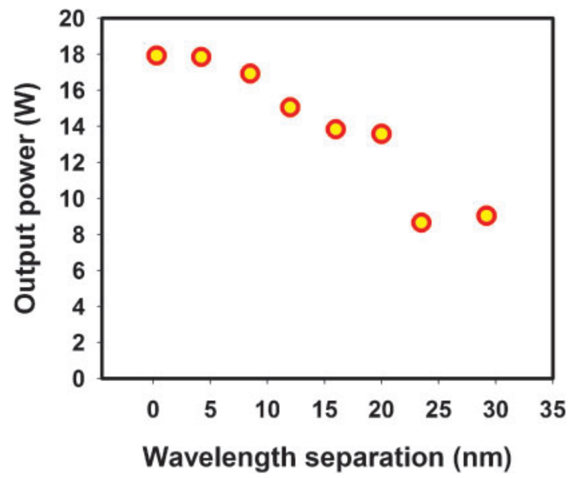

Fig. 4. Output power versus wavelength separation in dual-wavelength operating regime.

the system started lasing (see the inset in Fig. 2). Note that there is a pronounced decrease in the output power at the very ends of the wavelength tuning range, which results from the reduced gain at these wavelengths for the tested Er:Yb co-doped fiber. The measured output spectral linewidth (FWHM) was less than ~0.3 nm over the entire tuning range for each of the three VBGs.

On the basis of the tuning characteristics of the three VBGs, those with center wavelengths of 1545 and 1610 nm were selected to achieve relatively good lasing performance in the dual-wavelength tunable EYDFL; they are labeled VBG1 and VBG2, respectively. The resonators for the dual wavelengths were properly aligned, and independent wavelength tuning was realized by rotating the individual VBG and the corresponding HR mirror. To obtain a higher output power and broader dual-wavelength separation, we chose to tune from the center of the Er:Yb co-doped fiber's single wavelength tuning curve to the two ends by adopting a roughly equal spacing for the two wavelengths. In addition, the relative power ratio of the two lasing lines can be adjusted flexibly by proper control of their respective losses by slightly tilting the HR plane mirrors. Considering that multi-wavelength sources with lasing lines of equal power are strongly preferred and are required for many applications in optical communications and fiber sensors, dual-wavelength operation with roughly equal power for each wavelength was the focus of our experiment and was achieved by balancing the cavity loss for the two wavelengths. Figure 4 shows the total laser output power for the two wavelengths as a function of the corresponding wavelength separation at a launched pump power of 65.3 W. The output power gradually declined as the dual-wavelength separation grew from 0.3 to 29.2 nm, which is attributed mainly to the gain difference between the two wavelengths and the decrease in the effective reflectivity for VBGs aligned at a large angle. When one of the two operating wavelengths was tuned to a gain peak of around ~1545 nm (see the inset of Fig. 2), the large gain difference between the two wavelengths required a higher intracavity loss at the wavelength with a higher gain to balance their respective output power levels, resulting in a lower total output power instead. A much broader wavelength separation for the two wavelengths should be possible by the proper selection of the VBGs' center wavelengths with a much higher effective reflectivity in use. A maximum output power of 17.9 W, with equal lasing at 1552.8 and 1553.1 nm simultaneously, was obtained for a launched pump power of 65.3 W, which corresponds to a slope efficiency of 28.6% with respect to the launched pump power (see Fig. 5). No self-pulsation was observed even at the maximum output power. The short-term stability was measured to be <0.2% (RMS) on a time scale of 500 μs. The output power fluctuations remained below 0.7% over a time scale of 5 min. The relative power fluctuation for the two operating wavelengths remained below ~0.8 dB, and the corresponding wavelength shift was within 20 pm. The beam propagation factor (M^2) was measured to be ~2.5 with a beam profiler (Photon NanoScan). The two laser lines may have had different transverse modes owing to the multimode nature of the gain fiber we employed. As a comparison, the lasing characteristics of the EYDFL locked by the 1545 nm VBG arranged at normal incidence are also shown in Fig. 5. A higher output power of 21.9 W at 1545 nm was achieved with a slope efficiency of 34.2% because of the lower intracavity loss from a single VBG aligned at a normal incident angle.

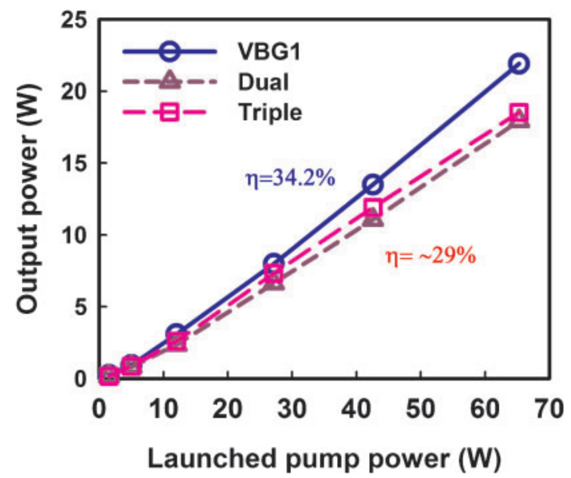

Fig. 5. Output power versus launched pump power in dual- and triple-wavelength-mode operation, with that of VBG1-locked fixed-wavelength operating regime for comparison.

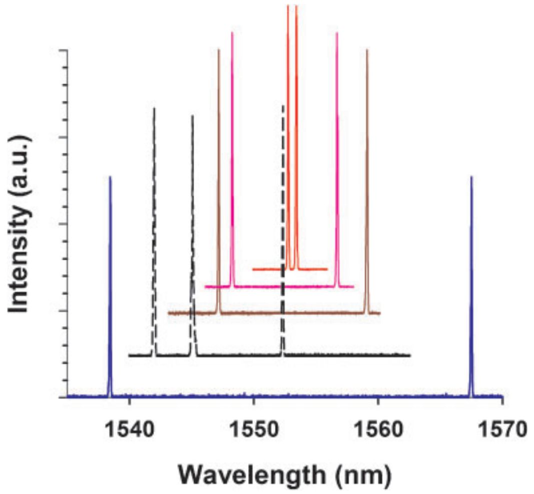

Fig. 6. Tuning spectra of dual-wavelength emission (solid colored lines) and spectrum of fixed triple-wavelength lines (black dashed line).

The technique demonstrated in this paper can be readily extended to multiwavelength operation owing to the broad gain profile of the Er:Yb co-doped fiber by simply adding more VBGs to the external cavity. The broad emission bandwidth of the Er:Yb co-doped fiber should allow oscillations of multiple operating wavelengths simultaneously because we did not observe any wavelength competition even at the smallest separation of 0.3 nm in the dual-wavelength operation mode. Actually, a smaller wavelength spacing can be obtained by using VBGs with a narrower spectral selectivity. To prove the feasibility of multiwavelength operation, the 1658 nm VBG and an additional HR plane mirror were also included to realize fixed triple-wavelength operation (lasing equally at 1542, 1545, and 1552 nm simultaneously). A total output power of 18.5 W was obtained, with a performance similar to that of dual-wavelength lasing at 1552.8 and 1553.1 nm in terms of the pump threshold and slope efficiency. Parasitic lasing of Yb^{3+} at ~1 μm was not observed even at the maximum launched pump power of 65.3 W. The output power showed a linear dependence on the launched pump power, suggesting that there is considerable scope to scale up the output power by simply increasing the pump power.

Figure 6 shows the tuning spectra of the dual-wavelength emission (solid colored lines) and the spectrum of the fixed triple-wavelength lines (dashed black line) recorded at a resolution of 0.1 nm. The measured output spectral linewidths (FWHM) for the dual or triple wavelengths were less than ~0.3 nm over the entire tuning range, which is comparable to the spectral linewidth of a single VBG's tuning spectrum.

In conclusion, we demonstrated high-power, dual-wavelength tunable operation of an EYDFL using two VBGs in a parallel arrangement. The wavelength splitting range of the two operating wavelengths was tuned continuously from 0.3 to 29.2 nm (0.04 to 3.7 THz), with a total output power of >13 W for a wavelength separation of <20 nm. A broader wavelength separation should be possible by selecting VBGs with the appropriate center wavelengths to reduce the intracavity loss. A maximum output power of 17.9 W was obtained at a wavelength separation of 0.3 nm for a launched pump power of 65.3 W, which corresponds to a slope efficiency of 28.6% with respect to the launched pump power. A third VBG and an additional plane mirror were also included in the external cavity to achieve triple-wavelength operation of the EYDFL with an output power of 18.5 W and equal lasing at 1542, 1545, and 1552 nm simultaneously, demonstrating the feasibility of multiwavelength operation of the EYDFL by simply adding more VBGs to the external cavity.

Acknowledgments This work was supported by the National Natural Science Foundation of China (NSFC 61078035 and 61177045), the Research Fund for the Doctoral Program of Higher Education of China (RFDP: 20110071110016), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

1) L. Talaverano, S. Abad, S. Jarabo, and M. Lopez-Amo, J. Lightwave Technol. **19**, 553 (2001).
2) T. Kleine-Ostmann, P. Knobloch, M. Koch, S. Hoffmann, M. Breede, M. Hofmann, G. Hein, K. Pierz, M. Sperling, and K. Donhuijsen, Electron. Lett. **37**, 1461 (2001).
3) M. Y. Jeon, N. Kim, J. Shin, J. S. Jeong, S.-P. Han, C. W. Lee, Y. A. Leem, D.-S. Yee, H. S. Chun, and K. H. Park, Opt. Express **18**, 12291 (2010).
4) Q. Mao and J. W. Y. Lit, IEEE Photonics Technol. Lett. **14**, 612 (2002).
5) Y. Liu, X. Dong, P. Shum, S. Yuan, G. Kai, and X. Dong, Opt. Express **14**, 9293 (2006).
6) T. Mizunami, T. V. Djambova, T. Niiho, and S. Gupta, J. Lightwave Technol. **18**, 230 (2000).
7) D. S. Moon, U.-C. Paek, and Y. Chung, Opt. Express **12**, 6147 (2004).
8) X. H. Feng, Y. G. Liu, S. Z. Yuan, G. Kai, W. Zhang, and X. Dong, Opt. Express **12**, 3834 (2004).
9) C.-L. Zhao, X. Yang, L. Chao, J. H. Ng, X. Guo, P. R. Chaudhuri, and X. Dong, Opt. Commun. **230**, 313 (2004).
10) Y. Liu, X. Feng, S. Yuan, G. Kai, and X. Dong, Opt. Express **12**, 2056 (2004).
11) O. Graydon, W. H. Loh, R. I. Laming, and L. Dong, IEEE Photonics Technol. Lett. **8**, 63 (1996).
12) S. Feng, O. Xu, S. Lu, X. Mao, T. Ning, and S. Jian, Opt. Express **16**, 11830 (2008).
13) X. H. Feng, H. Y. Tam, and P. K. A. Wai, Opt. Express **14**, 8205 (2006).
14) G. Y. Sun, D. S. Moon, A. X. Lin, W.-T. Han, and Y. Chung, Opt. Express **16**, 3652 (2008).
15) X. M. Liu, X. F. Yang, F. Y. Lu, J. H. Ng, X. Q. Zhou, and C. Lu, Opt. Express **13**, 142 (2005).
16) Z. G. Lu, F. G. Sun, G. Z. Xiao, P. Lin, and P. Zhao, IEEE Photonics Technol. Lett. **17**, 1821 (2005).
17) H. Ahmad, A. A. Latif, M. Z. Zulki, N. A. Awang, and S. W. Harun, Chin. Opt. Lett. **10**, 010603 (2012).
18) F. Wang, D. Shen, D. Fan, and Q. Lu, Opt. Lett. **35**, 2388 (2010).