Front. Optoelectron. China 2010, 3(1): 33–37
DOI 10.1007/s12200-009-0088-7

REVIEW ARTICLE

Novel performance of fiber lasers: tunable operation in visible range

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Abstract A review of the main physical processes important for frequency doubling of fiber lasers and the results of development by the Novosibirsk group of the fiber lasers operating from blue-green to yellow-red spectral ranges with a potential of the broad continuous tuning are presented. These lasers with ~100 mW power are treated to be attractive light sources for applications in medicine, especially in confocal microscopy and flow cytometry.

Keywords fiber laser, tunable operation, Raman fiber lasers (RFLs), frequency tuning, frequency doubling

1 Introduction

Fiber lasers have become popular and widely used in applications such as materials processing due to their high-power capabilities and extreme reliability based on fiber specifics: efficient laser diodes (LDs) pumping and air cooling, high-quality beam guided at low distortion and loss, and an all-fiber design with in-fiber cavity elements such as reflectors (fiber Bragg gratings, FBGs), couplers/splitters, frequency selectors, intensity modulators, etc. Typical rare-earth (RE) doped fiber lasers operate in near-infrared both in continuous wave (CW) and pulsed modes on the lines centered at ~0.92, ~1.1, and ~1.55 μm for Nd, Yb, and Er, respectively. Raman fiber lasers (RFLs) offer almost any wavelength in the range 1–1.7 μm by nonlinear frequency conversion of the RE fiber lasers output. The Raman process is very efficient even in conventional telecom fibers due to the high pump intensity concentrated in the microns-sized core along a km-long fiber that leads to efficient generation of the Stokes-shifted longer wavelengths.

One of the attractive opportunities for further development deals with frequency doubling of RE-doped and RFLs that offers operation in all visible range (450–850 nm), which may be tunable within the gain spectrum which is broad in silica glass of a fiber. Though several successful attempts on frequency doubling of Yb-doped and RFLs operating at fixed wavelengths are known [1,2], the developed techniques are hardly applicable for tunable operation.

A review of our developments of tunable fiber lasers operating in visible range is presented here. The developed low-power lasers are attractive for biomedicine.

2 Specifics of fiber lasers

2.1 Spectral broadening

The main problem for the efficient frequency doubling is the large linewidth of the fiber lasers especially for RFLs, which is also a result of a strong nonlinearity, but a negative one. We have studied spectral broadening in RFLs and have found its mechanism: multiple nonlinear four-wave mixing processes involving numerous longitudinal modes (up to ~10^6 in 1-km long cavity) and dispersion at propagation along the cavity result in stochastic evolution of their amplitudes and phases with a turbulence-like behavior. The developed analytical model [3,4] quantitatively describes spectra observed in RFLs with high-Q cavity formed by highly-reflective fiber Bragg gratings (FBGs), and provides very good approximation for the output spectra of high-power RFLs having relatively high transmission [5]. In spite of the narrow FBG reflection spectrum, the RFL spectrum at high powers acquires wide (2–4 nm) exponential tails that look like a "triangle" in logarithmic scale, as shown in Fig. 1 [5]. The developed model is not directly applicable to RE-doped fiber lasers, as they have much higher gain at much shorter length leading to a strong longitudinal inhomogeneity. Nevertheless, for a typical 10-m long cavity number of

Received August 1, 2009; accepted October 28, 2009

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modes is large enough (~10^4), and their nonlinear interaction in combination with dispersion lead to similar turbulence-like broadening, resulting in hyperbolic secant shape, but its spectral width is narrower (< 1 nm), as shown in Fig. 2 [5].

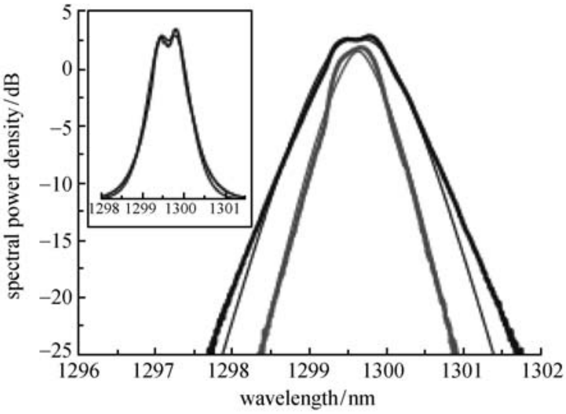


Fig. 1 RFL output spectra measured (thick curve) and calculated (thin curve) at 1 W (grey) and 2 W (black) of RFL output power (inset: spectra measured and calculated at 2.8 W in linear scale) [5]

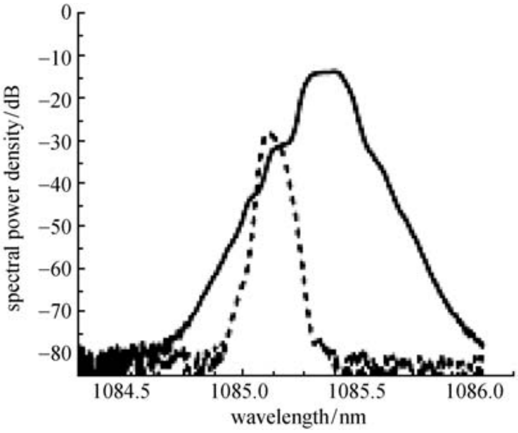


Fig. 2 Yb-doped fiber laser (YDFL) output spectrum at output power of 0.25 W (dashed line) and 7 W (solid line) [5]

2.2 Random polarization

Because of the strong spectral broadening, the cavity of a fiber laser formed with the help of relatively narrow-band FBG remains "leaky", i.e., it is difficult to increase intensity inside the cavity. As a result, the doubling efficiency appeared to be low at the first attempt of the intra-cavity frequency doubling [6]. Thus, usually single-pass schemes are applied for frequency doubling of fiber lasers, requiring very efficient nonlinear crystals, e.g., periodically poled (PP) crystals like PP lithium niobate (PPLN), etc. [1,2]. At the same time, such crystals have relatively small acceptance spectral width and convert only one polarization component. Thus, for efficient doubling special efforts are made resulting in a complicated fiber laser design [1,2], e.g., linearly polarized single-frequency distributed feedback (DFB) lasers in combination with amplifiers in a master-oscillator power-amplifier (MOPA) configuration is the usual solution [1]. In addition, it is difficult to tune the operating wavelength in such configuration.

We focus on alternative schemes of frequency doubling based on conventional fiber laser configurations that deliver random polarization with broad enough spectrum paying special attention to broad-range tuning potential.

3 Frequency doubling of YDFL

3.1 Intra-cavity frequency doubling

For RE-doped fiber lasers with relatively narrow output spectrum, it is more-or-less easy to satisfy phase-matching conditions at frequency doubling. The more important problem for these lasers is the polarization. For an efficient doubling one can use special polarization-maintaining fiber and PP crystals. However, we have applied a simpler solution: type II phase matching in $KTiOPO_4$ (KTP) crystals utilizing both polarization components of the randomly-polarized fundamental wave. It is known that walk off here may be compensated at selected wavelengths [7]. To further increase the efficiency of the doubling, we have applied intra-cavity schemes.

Maximum power of the Yb-doped fiber laser (YDFL) is reached at ~1080 nm. At the long-wavelength part of the Yb^{3+} gain curve, the intra-cavity scheme leads to ~3 times increase of the second-harmonic (SH) output power compared to the single-pass one, as shown in Fig. 3(a) [8]. At that, factor ~2 is due to double-pass conversion and factor ~1.5 is due to intensity enhancement inside the cavity compared to the same YDFL power with output coupler at the same pumping (~20 W LD at 976 nm). The low intensity enhancement coefficient is shown to be reasoned by the spectral broadening effects, which lead to significant increase of the highly-reflective FBG transmission (from 1% to 20% with increasing power), as shown in Fig. 3(b) [8], used as narrow-band cavity reflector. To reduce this effect we have applied large-mode area active fibers providing lower intensity at the same power thus decreasing nonlinear effects.

At the short-wavelength wing of the YDFL gain, the most important problem is the significant influence of absorption with maximum at 976 nm, which requires the use of shorter active fibers. As a result the efficiency of the YDFL is lower but at the same time frequency doubling efficiency enhancement in intra-cavity schemes becomes significantly higher and amounts to about one order of magnitude for 515 nm, as shown in Fig. 4(a) [9]. Because of shorter active length the spectral broadening induced by nonlinear effects is not so strong and transmission increases from 1% to 4% only, as shown in Fig. 4(b), which makes possible a ~4 times SH power increase due to the intra-cavity intensity enhancement at 1030 nm [9].

3.2 Tunable operation

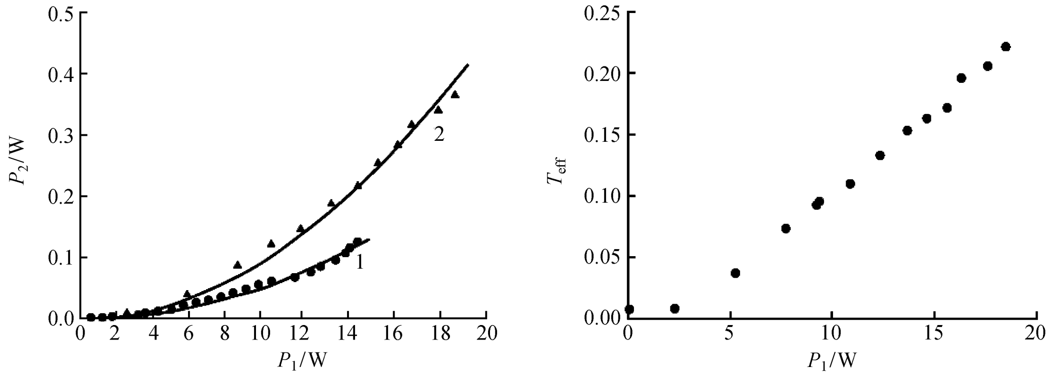
To realize tunable operation in visible range it is necessary to tune the fundamental wavelength and phase-matched wavelength of the nonlinear crystal synchronously.

First, we have developed YDFL continuously tunable within > 40 nm range in an all-fiber configuration by means of tunable fiber Bragg grating [10].

To tune the SH wavelength we checked a possibility to change the operating (phase-matched) wavelength by tilting the KTP crystal in the walk-off compensated geometry [7]. We have compared frequency doubling of the tunable YDFL with three KTP crystals in geometries differing by angle α between the crystal axis and its input surface. It has been obtained that the smaller the angle (i.e., closer to noncritical phase-matching), the higher the efficiency of frequency doubling, but at the same time its continuous tuning range is limited, as shown in Fig. 5 [11]. Mounting the crystal inside the YDFL cavity leads to output power increase as expected, but additional power modulation at the tuning appears, as shown in Fig. 6 [11]. It has been found that this variation is reasoned by the phase effects induced by dispersion of the intra-cavity elements, which may be compensated.

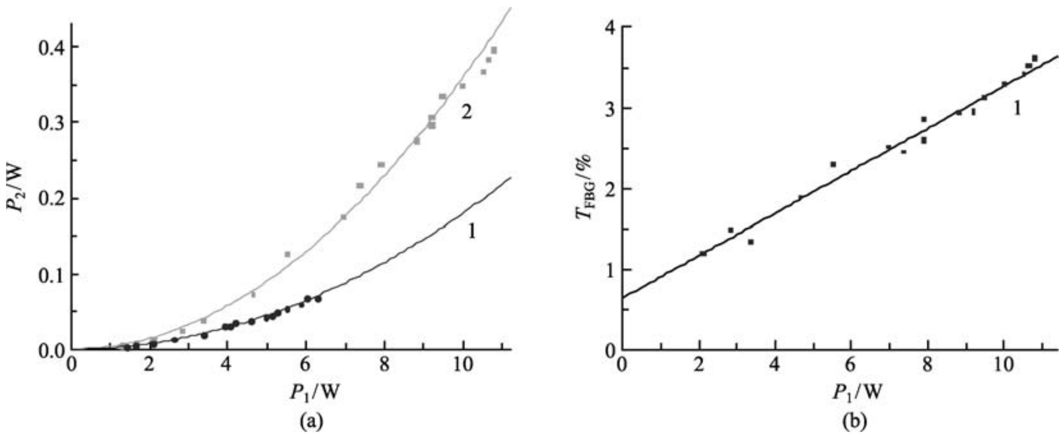
Note that the largest tuning range in the green (540–561 nm) has been reached for a crystal with $\alpha = 12°$, as shown in Fig. 5, which was limited by the YDFL tuning range.

Summarizing the results of the YDFL frequency doubling, the intra-cavity doubling scheme with KTP crystal in special configurations ~1 W power level has been reached with a choice of wavelengths in the blue-green range 515–560 nm. More than 20 nm continuous tuning with one KTP crystal has been demonstrated. In addition, Nd-doped fiber laser operation in the range 460–470 nm has been also obtained.



(a) (b)

Fig. 3 (a) SH power P_2 (at 542.5 nm) versus fundamental wave power P_1 in single-pass (1) and in intra-cavity (2) doubling schemes (for intra-cavity scheme, P_1 corresponds to running wave power; solid curves correspond to quadratic approximations); (b) measured effective FBG transmission $T_{\rm eff}$ versus YDFL intra-cavity power P_1 at 1085 nm [8]



(a) (b)

Fig. 4 (a) SH power P_2 (at 515 nm) versus fundamental power for single-pass (1) and intra-cavity (2) configurations; (b) effective FBG transmission coefficient versus intra-cavity YDFL power [9]

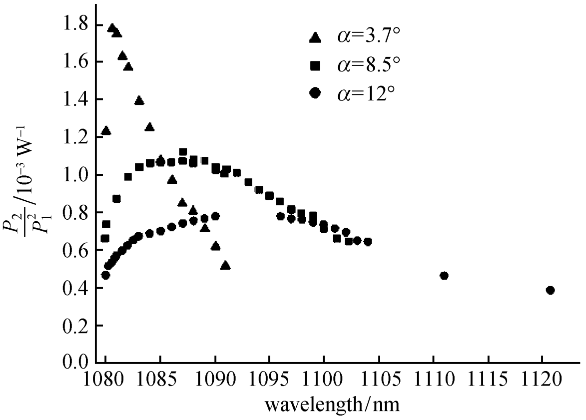


Fig. 5 Conversion coefficient P_2/P_1^2 versus fundamental wavelength for crystals with α = 3.7°, 8.5°, and 12° [11]

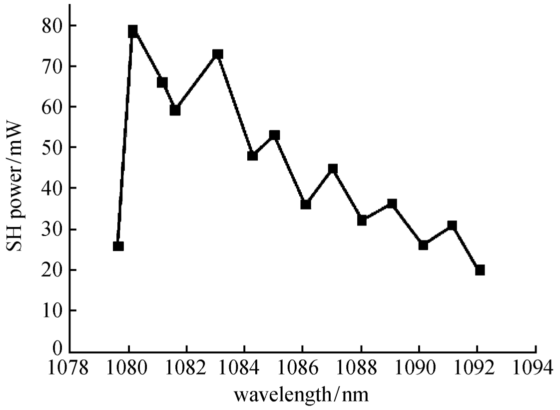


Fig. 6 SH power versus fundamental wavelength for intra-cavity frequency doubling in crystal with α = 3.7° [11]

4 Frequency doubling of RFLs

4.1 Frequency tuning

For RFLs we also studied possibilities to tune their wavelength as broad as possible and to convert it to visible (yellow-red) range in a simple and reliable configuration.

First, we have developed an all-fiber tunable RFL configuration. We applied a phosphorus-doped silica fiber as a Raman medium that provides conversion of ~1.1-μm pump (YDFL) to ~1.3-μm RFL output with one Stokes shift only [12]. Wavelength tuning is made by tunable FBGs like in YDFL. To increase tuning range we have realized in addition a synchronous tuning of the FBGs forming RFL and YDFL cavities. As a result, > 50 nm continuous RFL wavelength tuning has been obtained, see Fig. 7 [13].

4.2 Frequency doubling

We have studied the possibility of increasing frequency doubling efficiency with the broad spectrum.

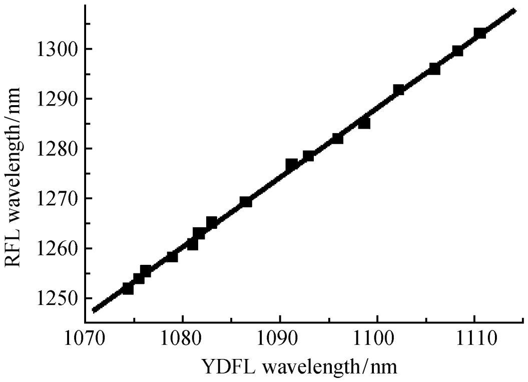


Fig. 7 Tunable RFL generation wavelength versus YDFL pump wavelength [13]

Utilizing PPLN in a simple single-pass scheme, a 655-nm laser radiation with a power of > 60 mW is generated by frequency doubling of a broadband randomly-polarized 7-W 1.31-μm RFL. The measured SH power increases nearly linearly with increasing RFL power, as shown in Fig. 8 [14]. Comparing the data with standard single-frequency model (dashed line) we revealed that the obtained SH values are even higher in low-power domain. Under these conditions the experimental SH wave spectrum is much narrower (< 0.3 nm full width at half maximum (FWHM)) than the fundamental wave generated by RFL (up to 1.6 nm) and nearly coincides with the PPLN crystal acceptance width being almost independent of power, as shown in Fig. 9 [14].

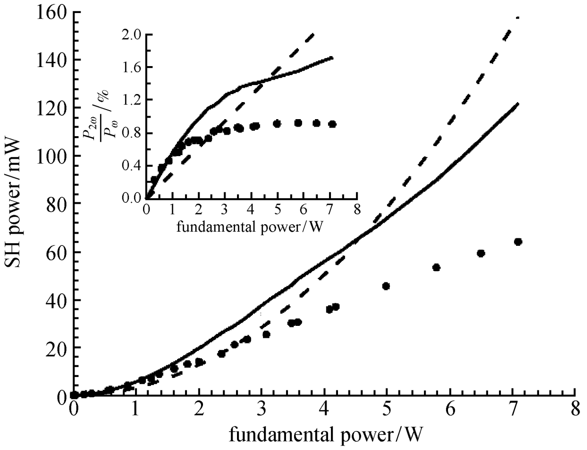


Fig. 8 Experimental data (points) and calculated SH power $P_{2\omega}$ versus $P_\omega = P_{\mathrm{RFL}}$ for single frequency (dashed line) and multiple frequency (solid line) fundamental waves (inset: corresponding SH generation efficiency $P_{2\omega}/P_\omega$) [14]

It has been found, that multiple sum-frequency mixing processes involving different RFL modes provide the main contribution to the SH output. In addition, the output is enhanced by 2 times due to the modes stochasticity specific to RFL. The developed sum-frequency model (solid line)

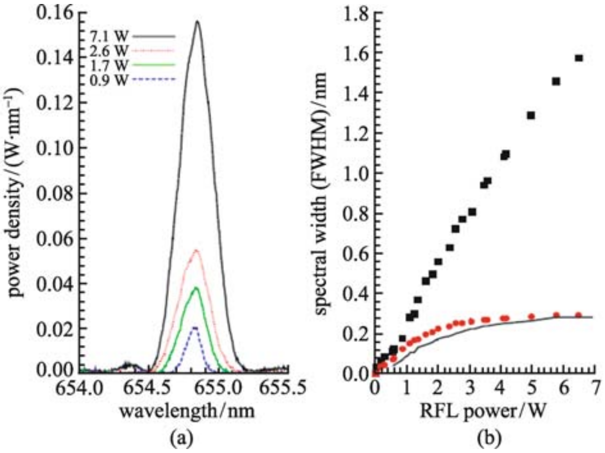


Fig. 9 SH output spectra measured at different RFL powers and fundamental wave (boxes) and SH (circles) spectral widths together with calculated curve [14]

agrees quite well with the experiment. This mechanism makes the doubling of broadband RFL spectra with random modes even more efficient than that for single frequency at moderate power. In combination with tuning, the developed phosphosilicate RFL may operate in the 625–655 nm range.

5 Conclusion

A robust platform for tunable fiber lasers operating from blue to red at ~100 mW power, which is enough for many applications such as biomedicine, has been developed. Though the efficiency of fiber lasers doubling is higher at high pumping power [1,2], the developed platform seems optimal in low-power domain advancing tunability in addition. For applications the most interesting are the possibilities to use these lasers as light sources in confocal microscopy and flow cytometry. The first tests have shown very good results [15].

Acknowledgements This study was supported by grants from the Russian Academy of Sciences, Russian Ministry of Education and Science, and Civilian Research and Development Foundation (CRDF); the development work was supported by Zecotek Photonics Pte. Ltd., Singapore.

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