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High-power, cascaded random Raman fiber laser with near complete conversion over wide wavelength and power tuning

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Abstract: Cascaded Raman fiber lasers based on random distributed feedback (RDFB) are proven to be wavelength agile, enabling high powers outside rare-earth doped emission windows. In these systems, by simply adjusting the input pump power and wavelength, high-power lasers can be achieved at any wavelength within the transmission window of optical fibers. However, there are two primary limitations associated with these systems, which in turn limits further power scaling and applicability. Firstly, the degree of wavelength conversion or spectral purity (percentage of output power in the desired wavelength band) that can be achieved is limited. This is attributed to intensity noise transfer of input pump source to Raman Stokes orders, which causes incomplete power transfer reducing the spectral purity. Secondly, the output power range over which the high degree of wavelength conversion is maintained is limited. This is due to unwanted Raman conversion to the next Stokes order with increasing power. Here, we demonstrate a high-power, cascaded Raman fiber laser with near complete wavelength conversion over a wide wavelength and power range. We achieve this by culmination of two recent developments in this field. We utilize our recently proposed filtered feedback mechanism to terminate Raman conversion at arbitrary wavelengths, and we use the recently demonstrated technique (by J Dong and associates) of low-intensity noise pump sources (Fiber ASE sources) to achieve high-purity Raman conversion. Pump-limited output powers >34W and wavelength conversions >97% (highest till date) were achieved over a broad – 1.1μm to 1.5μm tuning range. In addition, high spectral purity (>90%) was maintained over a broad output power range (>15%), indicating the robustness of this laser against input power variations.

1. Introduction

High-power fiber lasers have gained significant attention over the last decade for industrial, defense and medical applications. This is due to their superior beam quality along with power scalability, reliability and robustness [1]. However, conventional rare-earth doped fiber lasers are limited in terms of wavelength coverage and power scalability. Wavelength coverage is limited to fixed and narrow band emissions at 1μm, 1.5μm and 2μm corresponding to Ytterbium (Yb), Erbium and Thulium/Holmium (Tm/Ho). Power scalability is primarily confined to Yb emission window. However, there are number of applications requiring fiber lasers outside rare-earth emission bandwidths. In this regard, cascaded Raman fiber lasers are proven to be wavelength agile providing high-power fiber lasers outside rare-earth emission windows [2]. However, conventional systems [3–5] utilize fixed wavelength Fiber Bragg gratings (FBGs) for wavelength conversion which in turn fixes both input pump and output signal wavelengths. This limits the wavelength agility of these systems. Recently, cascaded Raman fiber lasers based on Random distributed feedback (RDFB) have been proposed which

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offer grating-free solution for wavelength conversion [6,7]. In these systems, by simply adjusting the input pump power and wavelength, high-power, ultra-widely tunable lasers have been demonstrated [8,9]. However, these systems have two major limitations which hinders their further power scalability and applicability. The first one is their limited degree of wavelength conversion or spectral purity, defined as percentage of output power in the desired wavelength band. The second one is the output power range over which, high degree of wavelength conversion or spectral purity can be maintained. The reason for low spectral purity in these systems is attributed to the intensity noise of the pump source used for Raman conversion. The effect of intensity noise effect is to substantially increase the Raman gain due to stimulated Raman scattering (SRS) [10] and because of ultra-fast nature of SRS process, the intensity noise of pump is directly transferred to the Raman Stokes orders. This leads to incomplete power transfer between Raman Stokes orders causing reduction in spectral purity. The reason attributed to the limited output power range over which high spectral purity can be maintained is the unwanted Raman conversion to the next higher order Stokes signal, with increasing power. Recently, use of temporally stable (low intensity noise) pump sources for Raman conversion has been demonstrated to increase the spectral purity [11]. Here, intensity noise properties of FBG based lasers was compared with fiber based amplified spontaneous emission (ASE) sources and having found them more temporally stable, were used as pump source and a spectral purity of >90% has been achieved up to 8th order Raman Stokes of 1691.6nm. the maximum power achieved in this system is ~7W at 1691.6nm. Even though such a result in itself is very attractive, however, in this system, there is no mechanism to maintain such a high degree wavelength conversion at higher power operations. This requires, termination of cascaded Raman conversion at any arbitrarily desired wavelength band, so that unwanted Raman conversion to the next Stokes order can be prevented. Termination of cascaded Raman conversion has been implemented previously at a fixed wavelength band of 1.5μm with the help of specialty Raman filter fiber [12]. Such specialty fiber has been utilized both in conventional cascaded Raman lasers [3–5], and in cascaded Raman lasers based on RDFB [13]. Also, natural termination due to enhanced intrinsic absorption losses of optical fiber [14] and the use of fiber-based Lyot filters in polarization maintaining systems [15] were demonstrated previously. However, all the previous methods work only at fixed wavelength bands and don’t work for a wavelength tunable configuration. Recently, we demonstrated a novel filtered feedback mechanism to terminate cascaded Raman conversion at any arbitrary wavelength band enabling a high-power, ultra-widely tunable, cascaded Raman fiber laser [16]. In this work, we combine both these significant developments – utilizing temporally stable pump source for cascaded Raman conversion, and filtered feedback mechanism to terminate Raman cascade at any arbitrary wavelengths. We demonstrate a high-power, cascaded Raman fiber laser which performs near complete wavelength conversion. Pump-limited output powers of >34W and wavelength conversions >97% were achieved over broad output power variations and is tunable over the entire 1.1μm to 1.5μm wavelength range.

2. Experimental setup

Figure 1 shows the experimental setup. The high-power cascaded Raman conversion module is similar to the one we recently demonstrated [16]. Here, input pump source is an in-house built high-power Yb doped fiber ASE source operating at 1064nm The pump source consists of 4 stages where, a broadband ASE seed is filtered before amplifying to ~88W in three stages. The 3 dB bandwidth of the ASE pump after the final amplification stage was ~2.5nm. For performance comparison with the ASE source as pump, a conventional FBG based source was used as well as indicated in the Fig. 1. A fused fiber 1117/1480nm wavelength division multiplexer (WDM) was used to couple the input pump source into cascaded Raman conversion stage and to spatially separate the backward propagating Raman Stokes signals from the incoming pump source. The coupled pump power into the cascaded Raman conversion module (after the WDM) was ~75W. A Raman fiber of length 340m with an effective area of 12μm2 and zero-dispersion wavelength beyond 2μm was used to provide Raman gain through SRS and to provide RDFB via Rayleigh backscattering. The reduction in coupled pump power is due to non-ideal WDM used (1117/1480nm) and the splice losses between Pump to WDM and WDM to Raman fiber. In the feedback path, short-pass filters with varying cut-off wavelengths were used as shown in Fig. 1 to provide filtered feedback. For Raman conversion up to 4th order Stokes (1310nm band), we have used bulk, thin-film based short-pass filters with cut-off wavelengths varying from 1125nm to 1350nm.

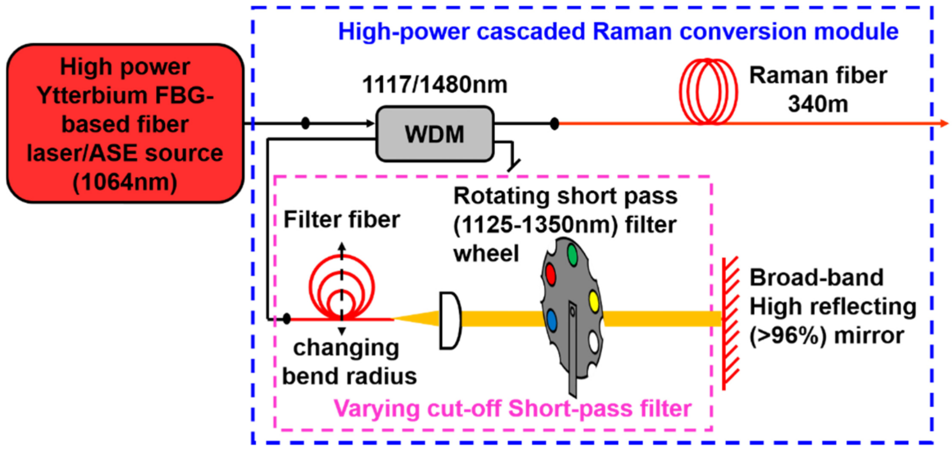

Fig. 1. Experimental setup of high-power cascaded random Raman fiber laser with near complete wavelength conversion.

These were mounted on a rotatable wheel to enable easily switchable configuration. Filtering for Raman conversion beyond the 4^{th} order (5th and 6th orders) was achieved with homemade filters based on coiling of filter fibers. The cut-off wavelengths of these filters can be varied from 1400nm and 1520nm. They were realized by winding the Raman filter fiber of length 5m with varying bend diameters from 1.2cm to 9cm. For terminating higher order Raman conversions, the filters need to be much sharper than necessary for lower order Raman conversions due to higher Raman gain. This is because, at higher order Stokes wavelengths, the amount of unconverted power increases at lower order Stokes wavelengths which reduces the maximum achieved spectral purity. In order to increase the spectral purity, we need to increase the Raman conversion from the lower order Stokes into the desired Stokes wavelength. This requires to increase input pump power while stopping the unwanted conversion of desired Stokes wavelength. This necessitates the use of filter fiber based filters which provide a much sharper and higher OD filters than thin-film based filters. This has been discussed in detail in [16]. A broad-band (800nm - 20μm), high reflecting (>96%) gold coated mirror was used to feed-back filtered backward propagating Raman Stokes signals into the cascaded Raman conversion stage. The optical density (OD) of bulk thin-film based short-pass filters used was >2, so in double-pass configuration, it is >4.

The working mechanism of the system is as follows, once the pump laser is switched on, cascaded Raman conversion occurs in both forward and backward direction inside the Raman fiber. Backward propagating signal consists of backward generated Raman Stokes signals and the RDFB of forward generated Raman Stokes signals. These signals get coupled into the cross-port of the WDM and the maximum coupling loss of ~24dBoccurs for 1117nm Stokes signal. However, because of high Raman gain (~80dB) the system easily overcomes the threshold and achieve lasing at all the stokes orders. All the Raman Stokes signals below the cut-off wavelength of the short-pass filter used will be fed back into the Raman conversion stage by the broad-band high reflecting mirror. Therefore, only the Raman Stokes signals below the cut-off wavelength of the short-pass filter will undergo further amplification and the Raman Stokes signals above the cut-off wavelength will be doubly attenuated by the

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short-pass filter. This increases the total losses for Raman Stokes signals above the cut-off wavelength of filter, which further suppresses their generation. In this way, very high-degree of Raman conversion can be achieved at the Stokes wavelength near to the cut-off wavelength of the filter. For performance comparison purpose, another in-house built FBG based Yb doped fiber pump laser with same power and bandwidth as ASE source was also used for cascaded Raman conversion.

3. Experimental results

Figure 2(a) shows experimentally measured in-band power ratios at maximum signal power as a function of wavelength using the ASE pump source (Solid lines) and with FBG based pump source (Dashed lines). In each case, the impact of feedback filtering is analyzed through looking at performance with and without feedback. In-band power ratios of >97% were achieved for all the Stokes wavelengths till 1480nm when ASE pump combined with filtering mechanism was used. The ratio however, was reduced to 92% when FBG based pump combined with filtering mechanism was used. Without the filtering mechanism, in-band power ratios of >92% were achieved for all the Raman Stokes orders, with the ASE pumping. But with FBG based pump, >95% was achieved only till 2nd order Stokes wavelength (1175nm). Figure 2(b) shows the maximum achieved in-band power as a function of wavelength. A maximum of >34W at 1480nm was achieved with ASE pump and filtering mechanism and it was reduced to ~28W without the filtering mechanism. This indicates that the two innovations incorporated here come with no reduction in output power, but rather enhances the output power.

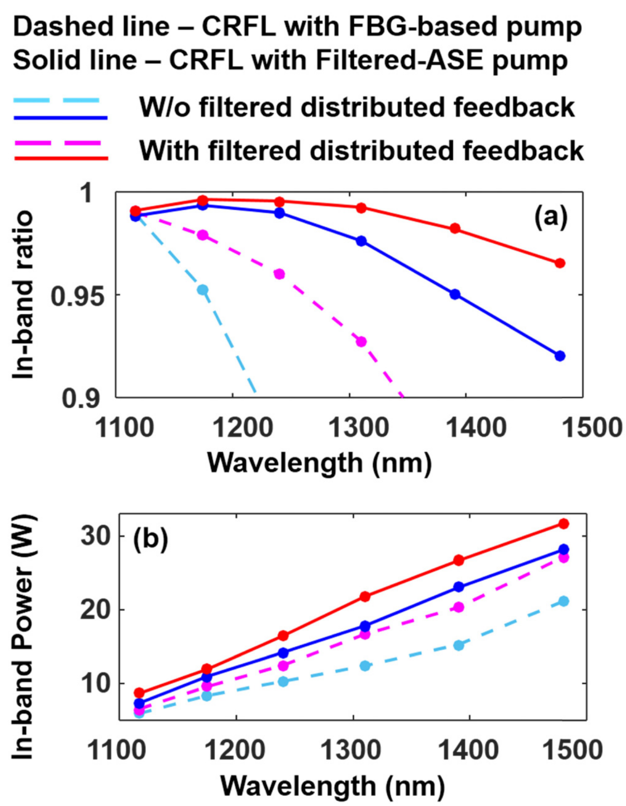

Fig. 2. (a) In-band power ratio vs wavelength for the different architectures. (b) In-band power vs wavelength in different architectures.

Similarly, with FBG based pump, maximum power of 27W with filtering mechanism and 21W without filtering mechanism were achieved at 1480nm. However, with FBG based

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pump, the spectral purity achieved was only 86% with filtering and 78.3% without filtering indicating low degree of wavelength conversion (see Fig. 3). The corresponding maximum efficiencies achieved for the case of ASE and FBG pumping with filtered feedback were 45.2% and 39.6% at higher order Stokes wavelengths (1480nm and 1390nm). At lower order Stokes wavelengths (1117nm and 1175nm) they are 44% and 43% with ASE pumping and 43% and 39.6% with FBG pumping.

Figure 3 shows the output spectrum (in linear scale) and the corresponding spectral purity at all Raman Stokes orders with ASE source pumping Fig. 3(a), and with FBG based source pumping Fig. 3(b). Also shown is the output spectrum at all Raman Stokes orders with filtering (left column for each pump case) and without filtering (right column for each pump case). Clearly, at lower Stokes orders, the difference in spectral purity for different cases is minimal. This is due to the use of long length of Raman fiber, which requires lower pump powers to generate lower Stokes orders. Lower the pump power, lower is the intensity noise and hence higher the spectral purity. However, at higher pump powers, FBG based pump source has higher intensity noise compared to ASE pump source. This drastically reduces the spectral purity to a maximum of 86% compared to 97% with ASE pumping. We also note that, for a given pump source, spectral purity or degree of wavelength conversion is maximized with the filtering mechanism as it prevents further Raman conversion. The demonstrated laser exhibits wavelength tuning from 1.1µm to 1.5µm with best spectral purity (degree of Raman conversion) of >97% demonstrated till date. The current system has discrete tuning due to a fixed wavelength input ASE source. However, this system can be easily configured to obtain continuous wavelength tuning as in [16] by using a tunable wavelength ASE pump source.

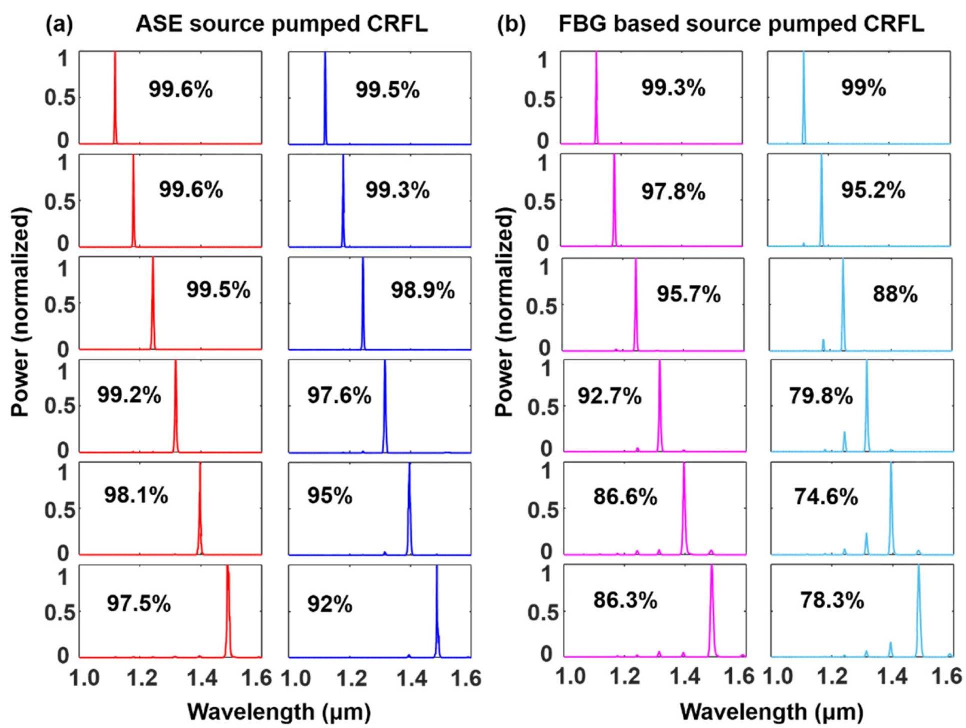

Fig. 3. Output spectrum at all the Stokes orders (left column: Red and Pink – with filtering, right column: Blue and Cyan – without filtering) of ASE source pumped CRFL (a); FBG based source pumped CRFL (b).

In order to study the importance of filtered feedback mechanism, we have plotted in Fig. 4, the evolution of in-band power ratio with respect to output power for all the Raman Stokes signals. For both ASE and FBG based pump sources, we measured in-band power ratio with and without filtering mechanism. As shown in the Fig. 2, for lower order Raman Stokes signals (till 2nd order, 1175nm), the maximum attainable in-band power ratio is comparable for both the pump cases with and without filtering. The reason as previously described is that, for longer lengths of Raman fiber, smaller pump powers are sufficient to generate lower order Raman Stokes signals. However, the effect of filtering is not just maximizing the in-band power ratio for a given pump source, it also helps in maintaining that in-band power ratio over longer output power ranges. This has two benefits – the laser is robust to variations in input power and this enables tuning of the output power while maintaining high degree of wavelength conversion. As clearly seen in Fig. 4, the flat band region of red curve (ASE with filtered feedback) is wider than all other curves. For instance, >90% in-band ratio is maintained for an output power ranging from 29W to beyond 34W at 1480nm with ASE pump combined with filtering. However, it is only from 29W to 30W of output power, without the filtering case. Similarly, at 1390nm Raman Stokes signal, the range is from 23W to 28W with filtering and from 23W to 24W without filtering for ASE pump case. Due to strong double-pass attenuation of backward propagating Raman Stokes signal (above the cut-off wavelength) by the short-pass filter, the threshold of generation for next higher order Raman Stokes signal is enhanced. This increases the output power range where high spectral purity is achieved. With the FBG based pump case, >90% in-band power ratio was achieved only till 4th order (1310nm) Raman Stokes with the filtering, and the output power range is from only 16W to 18W. without filtering, >90% in-band power ratio was achieved only till 2nd order Raman Stokes signal and the output power range is from 8W to 9W. We also note that even in the presence of filtering mechanism, at higher powers, the in-band power ratio suddenly drops below 90%. This is because, at high enough powers, the feedback due to Rayleigh backscattering of both forward and backward propagating Raman Stokes signal also increases and reduces the impact of filtering in the feedback path.

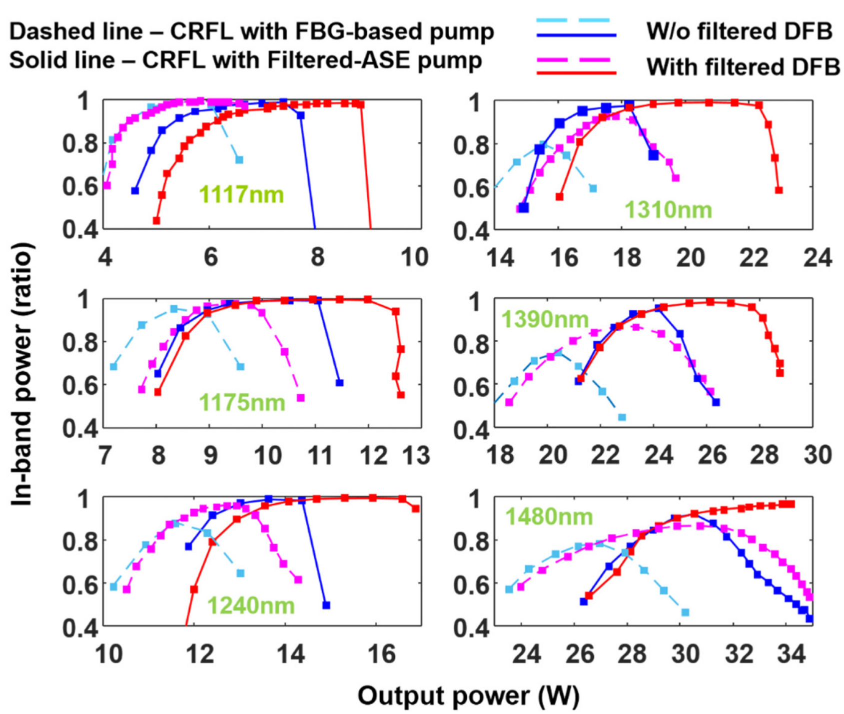

Fig. 4. In-band ratio evolution of all Raman Stokes signals with respect to output power for ASE and FBG based pump cases combined with and without filtering. DFB – distributed feedback.

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The property of maximum spectral purity for broad output power ranges is an important property to have for these laser systems as it indicates the high degree of robustness against input pump power fluctuations and the ability to tune output powers at a fixed wavelength. We quantify this property by the ratio of output power range where the spectral purity is >90% to the mean value of this range. The results are shown in Fig. 5(a). At 1480nm Stokes signal, >15% changes in the output power due to variations in the input pump power and/or due to power tuning will still ensure that the output spectral purity is >90%. This however was reduced to <3% without the filtering case. This substantial enhancement was fully enabled by the filtered feedback. With the FBG based pump combined with filtering mechanism, a maximum of 6% was achieved at 1310nm, and it is ~1% at 1175nm without the filtering mechanism. These results suggest that combined effect of using temporally stable pump sources cascaded Raman conversion and filtered feedback mechanism to terminate Raman cascade ensures a high performance and robust operation of these systems. Finally, we also measured the linewidths of different Raman Stokes orders at the points of highest spectral purity. The results are plotted in Fig. 5(b) for ASE pump combined with and without filtering mechanism. The linewidth of a particular Stokes is higher with filtering mechanism. The reason is attributed to the nonlinear effects like Self Phase Modulation (SPM) and broadband nature of Raman gain which broadens the Raman Stokes signal at higher power operations. However, in the case of no filtering mechanism, as the output power increases, the power gets transferred to next Raman Stokes order as its threshold is smaller compared to the scenario with filtering. The power in a particular Raman Stokes order is higher in case of filtered feedback and thus the linewidth is higher. A maximum linewidth of ~8.6nm with filtering and ~7.2nm without filtering was measured. The linewidths (not shown) when FBG based pump combined with and without filtering were higher (>10nm) compared to ASE pump case. This is because of higher intensity noise increases nonlinear broadening due to SPM.

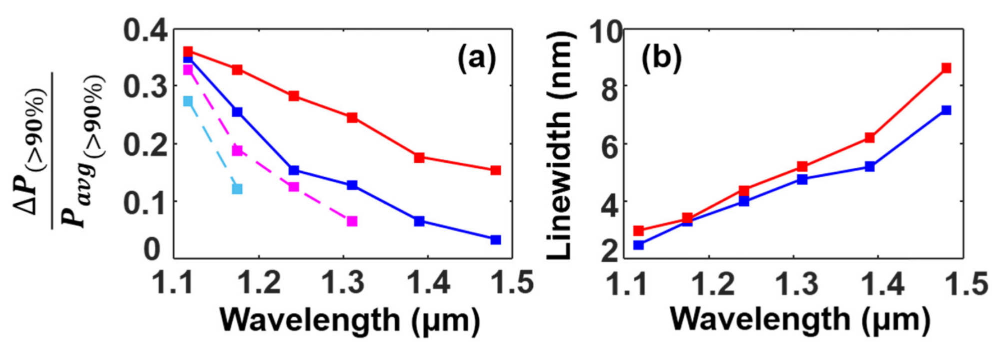

Fig. 5. (a) Ratio of the width of output power range with spectral purity >90% to the mean of this range for all the Raman Stokes orders with ASE and FBG pumping with and without filtering; (b)Linewidths of different Raman Stokes orders at maximum spectral purity for ASE pump combined with and without filtering.

4. Summary and conclusions

In summary, we have demonstrated a high-power (>34W), RDFB cascaded Raman fiber laser which performs almost complete (>97%, highest till date) Raman conversion starting with 1064nm Yb fiber ASE pump source. Such high degree of Raman conversion was achieved over a broad output wavelength range from 1.1μm to 1.5μm. Also, our system maintains high degree of Raman conversion (>90%) over broad output power range (>15% even at the 6th Raman cascade order) and hence achieves high tolerance against input pump fluctuations and enables output power tuning. Our work was the culmination of two significant developments in the field of cascaded Raman fiber lasers. Firstly, the use of temporally stable (low intensity noise) pump sources for Raman conversion, which enables high-spectral purity Raman Stokes orders. In this work, we used Yb fiber ASE source operating at 1064nm as a pump source. Secondly, the use of filtered DFB mechanism to terminate cascaded Raman conversion at any arbitrary wavelength. This maximizes the spectral purity obtained with low intensity noise pump source and helps in maintaining it over broad range of output powers. In this work, the results shown are for broadband discrete wavelength tuning from 1.1μm to 1.5μm. This is due to the use of a fixed wavelength input ASE source. However, this system can be easily configured to obtain continuous wavelength tuning as by using a ASE pump source tunable in the Ytterbium emission window.

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