Flat Amplitude Equal Spacing 798-Channel Rayleigh-Assisted Brillouin/Raman Multiwavelength Comb Generation in Dispersion Compensating Fiber

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***Abstract*—In this letter, we demonstrate a simple method of generating evenly spaced multiwavelength Brillouin comb by employing dispersion compensating fiber both for Brillouin Stokes generation and Raman amplification. Multiwavelength output of 798 Brillouin Stokes lines with average channel power of −17 dBm has been obtained with excellent flatness. Channel spacing corresponds to the Brillouin Stokes shift in dispersion compensating fiber and is estimated to be 9.4 GHz with the heterodyne detection method. Coupled interaction of Brillouin, Raman, and Rayleigh scattering explains the unique feature of proposed structure.**

***Index Terms*—Brillouin scattering, nonlinear optics, optical fiber devices, raman scattering, rayleigh scattering, wavelength-division multiplexing.**

I. Introduction

FOR THE FUTURE application to dense wavelength-division-multiplexing (DWDM) transmitter/characterization/reference sources and fiber sensors, there have been continuous efforts to generate multiwavelength comb from a cost-effective single light source. One of such approaches used optical frequency comb generator, which is based on an electrooptic modulator enclosed in a high finesse optical cavity driven by microwave with a constant frequency, and expanded the generated combs by using the nonlinear self-phase modulation (SPM) in dispersion flattened fiber (DFF) [1]. A slight different version of this scheme, which used mode-locked laser and DFF to generate supercontinuum source also have been tested successfully in 25-GHz spacing 10-Gb/s DWDM systems [2].

At the same time, totally different approaches have been accomplished by either utilizing comb filters or Brillouin Stokes shifts to acquire an even spacing in the generated optical spectrum, while making use of the erbium-doped fiber amplifier (EDFA), stimulated Brillouin process, or their hybrid in the amplifying medium [3]–[5]. Of these approaches, the most recent trends were for the multi-Stokes generation with fiber lasers, utilizing the inherited low threshold power and narrow channel spacing of stimulated Brillouin process. To enhance the feedback for successive higher order Stokes generation, multiwavelength Brillouin/Erbium fiber lasers (BEFL) with complex feedback schemes have been suggested. These include the recent demonstration of 53-line multiwavelength operation of BEFL [5]. However, all these past approaches for the generation of multiwavelength Brillouin Stokes lines had to employ rather complex structure to enhance the feedback mechanism, failing to provide cost effectiveness and good stability. Furthermore, homogeneous nature of gain medium (EDFA) limits the bandwidth and amplitude envelope profiles of the output comb spectrum.

In this letter, we set a new record on the number of output channels from an unmodulated single optical source, by employing a simple, but novel use of Raman amplification and other nonlinear processes within the fiber medium. 798 lines of Brillouin Stokes generation with high stability and excellent flatness have been realized from a single fiber section by employing a single-pass configuration.

II. Experiment

The experimental setup for the operation of multiwavelength generation is shown in Fig. 1. Raman gain in the range of 1550–1600 nm was provided using a high-power pump laser module. This high-power pump laser module is realized by using high-power Ytterbium fiber laser (maximum output power of 10 W) and seed pump lasers at wavelength band of 1400 nm. To assist the cascaded Raman Stokes generation to the desired pump bands, aluminum-coated fiber mirror is inserted for additional seed supply. As a low-threshold highly nonlinear Raman/Brillouin gain medium, small core size dispersion compensating fiber (DCF) has been used. To initiate the Brillouin process, a narrow linewidth tunable external cavity laser (ECL) was employed as a Brillouin pump source.

The principle of multiwavelength comb generation can be explained by coupled interaction of three nonlinear scattering processes. As the power of Raman pump lasers increase, injected Brillouin pump power exceed the Brillouin threshold. The feedback for multiple Stokes generation is provided by frequency-shifted Brillouin scattering, and frequency unshifted Rayleigh scattering and Raman gain is provided both for the amplification of the Brillouin and Rayleigh scattered power.

Fig. 2. shows the measured output spectrum of frequency comb generator. 742 Brillouin Stokes lines of over 57.2 nm

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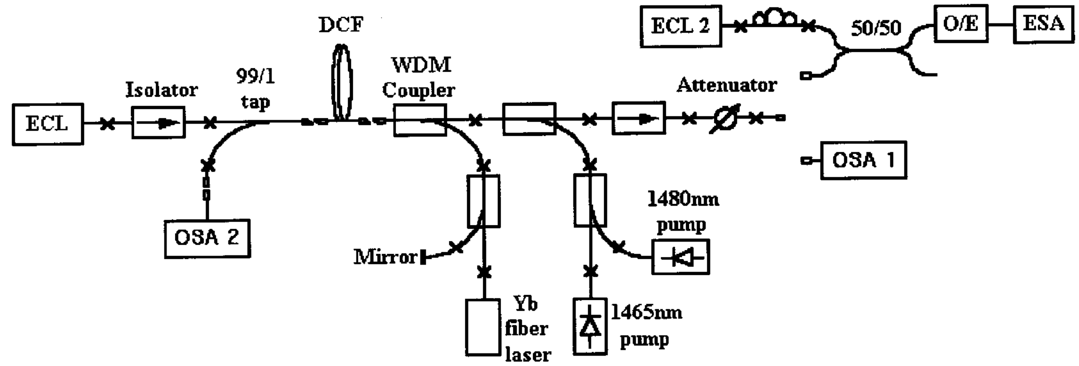
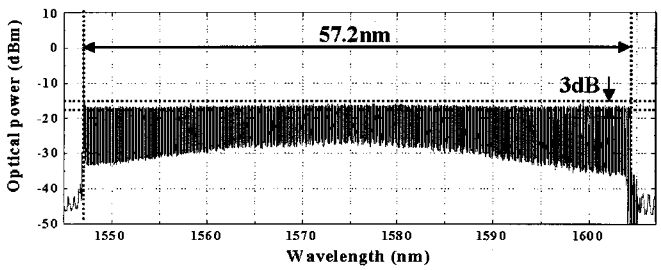
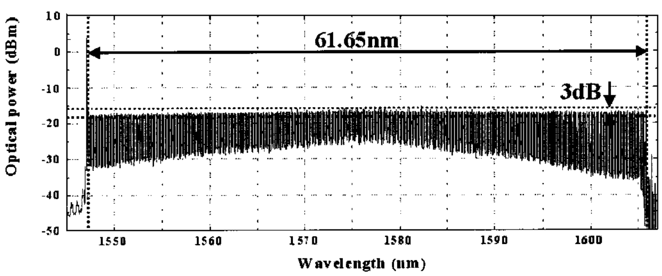


Fig. 1. Experimental setup for multiwavelength comb generation and measurement.



(a)

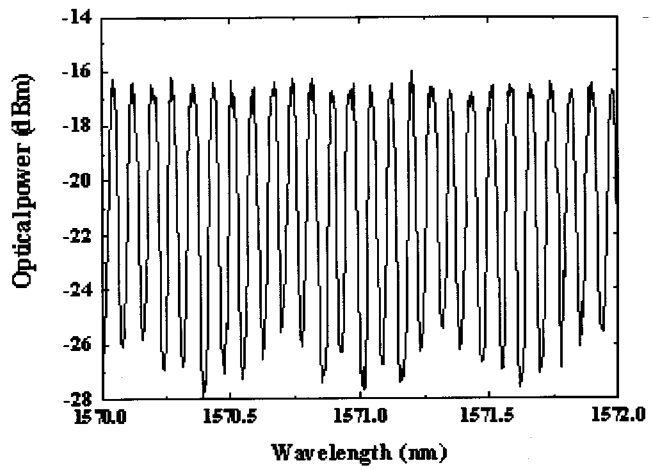


(b)

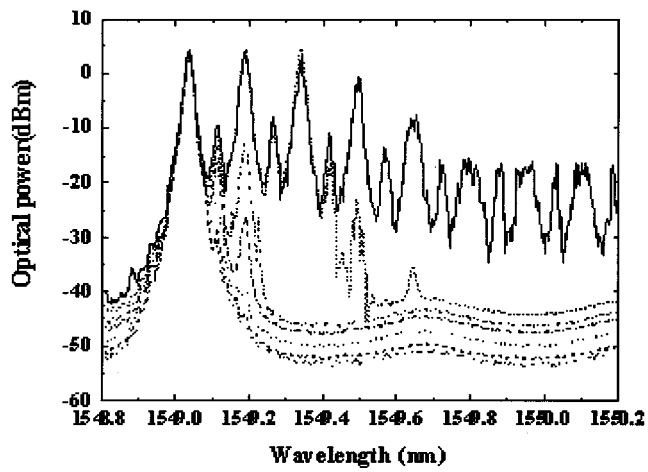
Fig. 2. (a) 742-line mutiwavelength comb spectrum (best flatteness). (b) 798-line mutiwavelength comb spectrum (maximum number of lines).

have been generated within 3-dB bandwidth (with best flatness among successive experiments) at the Brillouin pump wavelength of 1547.07 nm [see Fig. 2(a)]. Following a proper optimization procedure with a sacrifice on the flatness of envelope profile (still within 3 dB), 798 Stokes lines operation of over 61.65 nm was also obtained by changing the Raman and Brillouin pump powers [see Fig. 2(b)]. Here, the resolution bandwidth of optical spectrum analyzer (ANDO, AQ6317B) was 0.01 nm, and the average power was −17 dBm per channel. This excellent flatness and stability is partly due to the inhomogeneous nature of the Raman gain medium and the saturation characteristics of Brillouin amplification. The inner structure or detailed spectrum of the comb is shown in Fig. 3(a). Isolation of each Stokes line is clear, and the amplitude variation between neighboring channels was negligible. Due to the limited resolution bandwidth (0.01 nm) of the optical spectrum analyzer, it was impossible to further resolve the isolation/extinction depth of each peak. A full measurement of relative intensity noise is now being conducted and should be characterized further.

Fig. 3(b) illustrates the onset of Stokes generation as the Ytterbium fiber laser power increases (from 2.8 to 5.0 W). Ob-



(a)



(b)

Fig. 3. (a) Detailed spectrum of multiwavelength comb. (b) Comb generation as the power of Ytterbium fiber laser increases.

served is the threshold behavior between the *comb generation* and the pump power, meaning that this is not a simple reflection/amplification event. There are power discrepancies in the odd and even numbered Stokes lines in first few lines. This region seems to be in a Brillouin pump dominant regime. After these first few lines, the balance between three scattering processes leads to a flattened comb generation. The reason for the bandwidth differences between even and odd numbered lines in Fig. 3(b) seems to be originated from the distinct bandwidth

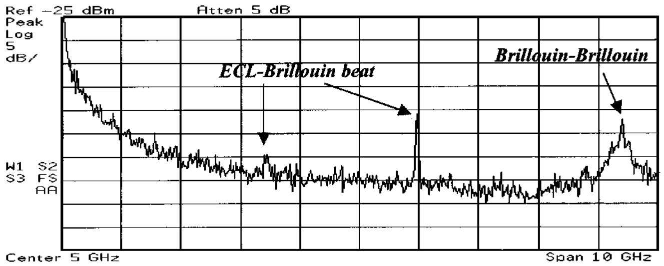


Fig. 4. RF spectrum of beating of the multiwavelength comb with ECL.

and threshold characteristics of Brillouin/Rayleigh scattering [6]. To measure the linewidth of the generated frequency comb, the output of the comb generator has been fed to a 3-dB coupler together with an additional external cavity laser, which was tuned to approximately between the centers of two comb frequencies (Fig. 1). Fig. 4 shows the RF spectrum measured with a high-frequency RF spectrum analyzer, with a 20-GHz unamplified O-E converter. Here, the peak at 9.4 GHz is a cumulative beating signal generated from the convolution of neighboring Stokes combs, and the peaks at 5.98 and 3.42 GHz are from ECL beating with nearest neighbor Stokes combs ($5.98+3.42 = 9.40$).

III. Conclusion

We demonstrated 798-line multiple wavelength comb generation using a simple, but novel design using a segment of fiber both for Brillouin, Rayleigh, and Raman scattering medium. Without complex optimization process, we easily obtain highly stable multiwavelength comb with excellent amplitude flatness. With proper pump arrangements, it should be straightforward to extend the number of comb frequencies beyond thousands. Adjustments on the comb shift frequencies can be achieved with optimizations on the fiber structure/doping material. The predetermined wavelength stability, and expandable flat spectrum with multiple Raman pumps over any wavebands will promise its applications for secondary wavelength standards and terahertz beat frequency generation in near future.

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