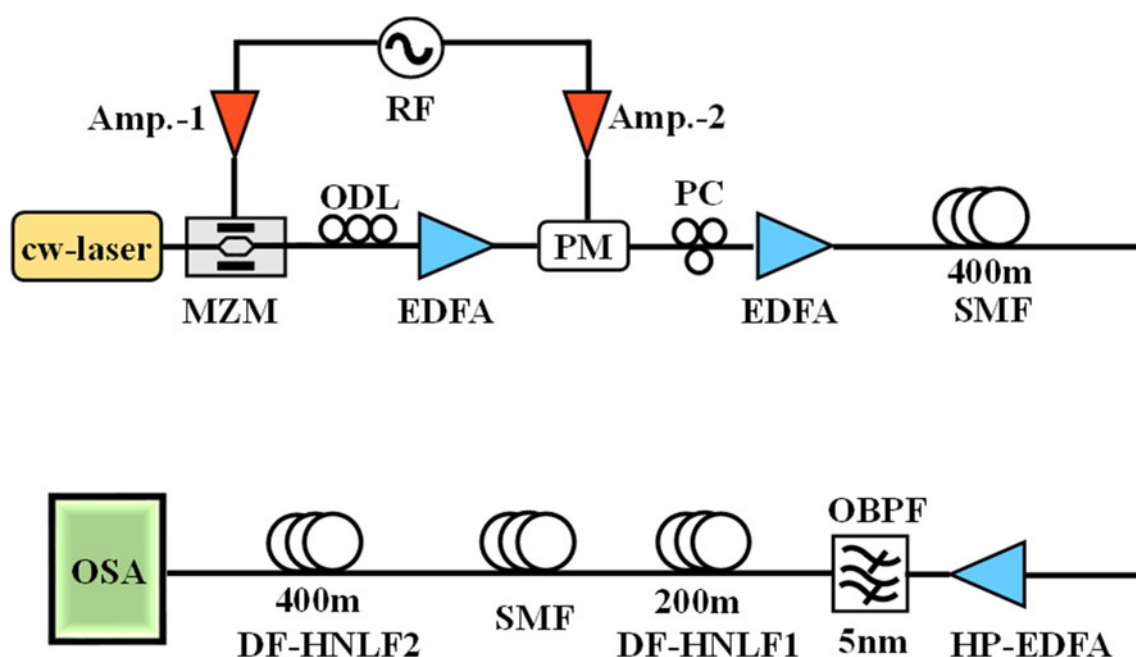


Broadband Optical Frequency Comb Generation With Flexible Frequency Spacing and Center Wavelength

Volume 10, Number 3, June 2018

Siyuan Yu
Fangdi Bao
Hao Hu



DOI: 10.1109/JPHOT.2018.2832842
1943-0655 © 2018 IEEE

Broadband Optical Frequency Comb Generation With Flexible Frequency Spacing and Center Wavelength

Siyuan Yu,¹ Fangdi Bao ^{1,2} and Hao Hu ²

¹National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China

²DTU Fotonik, Technical University of Denmark, Kgs. Lyngby 2800, Denmark

DOI:10.1109/JPHOT.2018.2832842

1943-0655 © 2018 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Manuscript received April 3, 2018; revised April 24, 2018; accepted April 28, 2018. Date of publication May 4, 2018; date of current version May 21, 2018. Corresponding authors: F. Bao and Hao hu (e-mail: 13b921023@hit.edu.cn).

Abstract: A broadband optical frequency comb with a flexible frequency spacing and a center wavelength is proposed and experimentally demonstrated. The proposed scheme consists of a single continuous-wave laser, cascaded Mach–Zehnder modulator (MZM) and phase modulator (PM), two-stage dispersion-flattened highly nonlinear fibers (DF-HNLFs), and a single-mode fiber in between. A narrow-band frequency comb is generated in the MZM and PM, and a broadband frequency comb is achieved by a self-phase modulation based spectral broadening in the DF-HNLFs. Since the DF-HNLF has low dispersion over a wide wavelength range, the central wavelength of the generated frequency comb can be tuned from 1535 to 1564 nm. In addition, the central wavelength of frequency comb has a potential to be extended to L-band according to the dispersion profile of the DF-HNLF and the operation bandwidths of the MZM and PM. By tuning the driving radio-frequency signal, the frequency spacing of the generated frequency comb can be tuned. In the experiment, the frequency spacing of 25 and 40 GHz has been achieved.

Index Terms: Fiber non-linear optics, frequency combs, fiber optics systems.

1. Introduction

The past several years have witnessed a phenomenon that optical frequency combs have been investigated in numerous applications such as metrology [1], [2], spectroscopy [3], optical communications [4] and terahertz (THz) wireless technology [5] and the chaotic systems [6]. In particular, high-quality frequency comb has recently become promising for coherent communications, offering a large number of optical carriers for wavelength-division multiplexing (WDM) transmission system [7]–[10]. The tones of a frequency comb are intrinsically equally-spaced in frequency. In addition, the mutual carrier coherence from the same source can also facilitate efficient mitigation of fiber nonlinearity in the transmission [11].

A typical technique to generate broad-band frequency comb is based on mode-locked lasers (MLL) [12], [13], however, the tunability in terms of center wavelength and frequency spacing is severely limited. Another approach for frequency comb generation is based on electro-optic modulators, which has been demonstrated with flexibility and tunability of frequency spacing and center wavelength [14]–[16]. Although these demonstrations show the tunability of frequency comb without compromising the complexity of the system, one common disadvantage is the generated

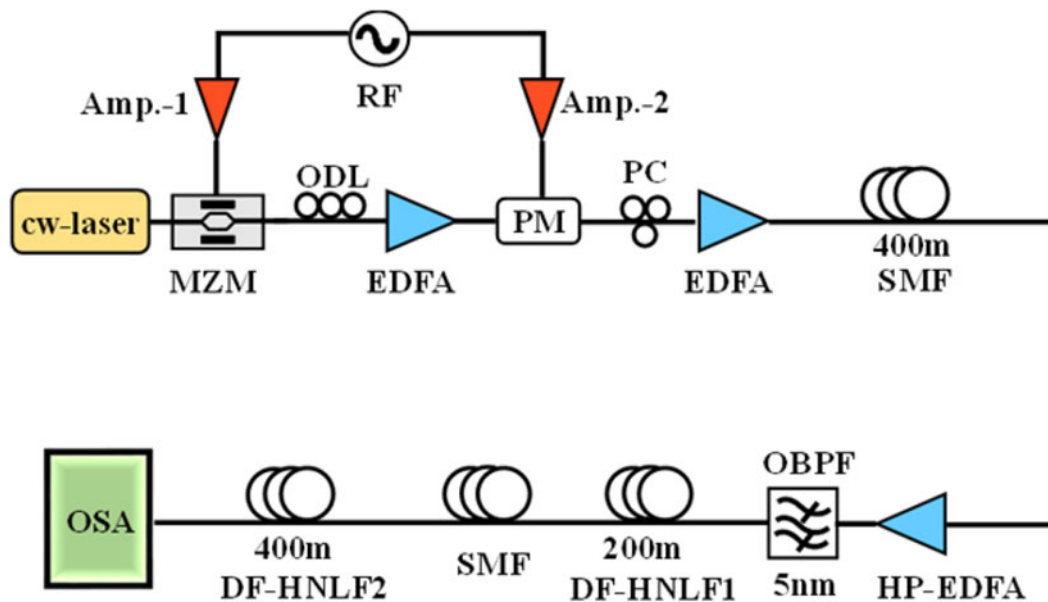


Fig. 1. Experimental setup of generating broad-band optical frequency comb with tunable center wavelength and frequency spacing. CW-laser: continuous-wave laser, RF: radio frequency, PM: phase modulator, MZM: Mach-Zehnder modulator, ODL: optical delay line, EDFA: erbium-doped fiber amplifier, PC: polarization controller, Amp.: Amplifier, SMF: single mode fiber, HP-EDFA: high-power erbium-doped fiber amplifier, OBPF: optical bandpass filter, DF-HNLF: dispersion-flattened highly nonlinear fiber, OSA: optical spectrum analyzer.

comb has a rather narrow bandwidth. To achieve a broad-band frequency comb, nonlinear spectral broadening based on self-phase modulation in a highly nonlinear fiber (HNLF) is usually needed [17]–[19]. However, this usually leads to limited tunability of the center wavelength of the frequency comb, since the center wavelength of the input pulse is usually required to be close to the zero-dispersion wavelength of the HNLF. So far, a broadband frequency comb with widely tunable center wavelength and frequency spacing has not been demonstrated yet.

In this paper, we experimentally demonstrate a broad-band frequency comb with widely tunable center wavelength and frequency spacing, using cascaded electro-optic modulators and dispersion-flattened (DF)-HNLFs. In our scheme, a continuous-wave (CW) light is modulated by a Mach-Zehnder modulator (MZM) and a phase modulator (PM), which is compressed into a short pulse by passing through a dispersive element, and then launched into two-stage DF-HNLFs for frequency comb spectral broadening. Since the DF-HNLF used in the experiment has a low dispersion over a broad wavelength range, it allows for the tunability of the center wavelength. Frequency spacing can be tuned by changing radio-frequency (RF) signal. In this experiment, the broad-band frequency comb with the wavelength tunability from 1535 nm to 1564 nm and frequency spacing of 25 GHz and 40 GHz has been achieved. For the 25-GHz frequency spacing, the generated frequency comb has a 30-dB bandwidth of 125 nm, 132 nm and 132 nm at the central wavelength of 1535 nm, 1550 nm and 1564 nm, respectively; for the 40-GHz frequency spacing, the generated frequency comb has a 30-dB bandwidth of 155 nm, 155 nm and 164 nm at the central wavelength of 1535 nm, 1550 nm and 1564 nm. Furthermore, we also investigate the bandwidth of the broadened frequency comb for different launched powers into the DF-HNLFs.

2. Experimental Details

The block diagram of the experimental setup for broad-band frequency comb generation with tunable center wavelength and frequency spacing is shown in Fig. 1. A CW light emitted from a tunable laser is modulated by cascaded MZM and PM, which are driven by a RF sinusoidal signal. By changing

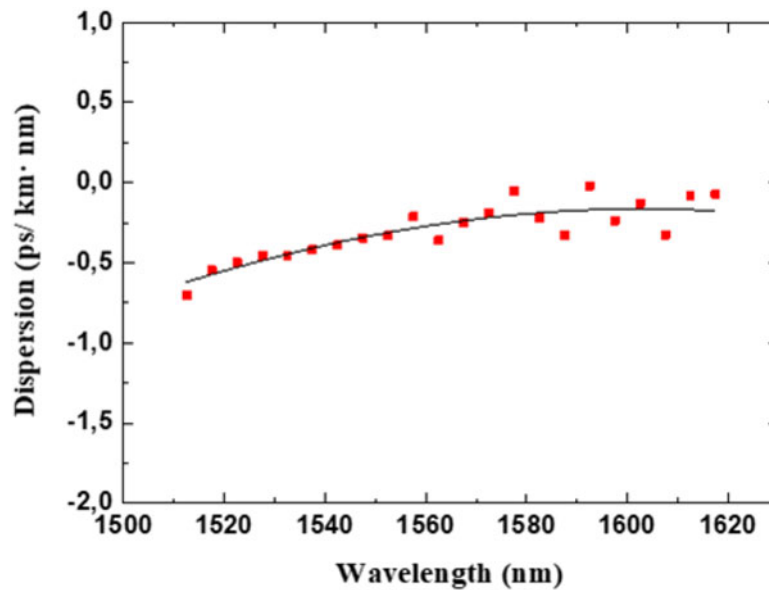


Fig. 2. Dispersion profile for the dispersion-flattened highly nonlinear fiber (DF-HNLF).

the frequency of the driving RF signal, the frequency spacing of the generated frequency comb can be adjusted. By adjusting the delay line in between the MZM and the PM, the positive chirp generated in the PM is reserved and the negative chirp is removed due to pulse carving in the IM [20]. The positive chirp is then compensated by passing through a 400 m single mode fiber (SMF) and the pulse is compressed into a short pulse with a full width at half maximum of 2.5 ps. The short pulse is amplified by a high-power EDFA (HP-EDFA) and filtered by a 5-nm bandpass filter before launching into DF-HNLFs. Based on the self-phase modulation (SPM), broad-band frequency comb is generated in the DF-HNLFs. In this experiment, two-stage DF-HNLFs with the same physical property but different lengths of 200 m and 400 m are used. A single mode fiber (SMF) is inserted in between two DF-HNLFs in order to compensate the dispersion of the DF-HNLF1. The pulses at the output of the DF-HNLF1 are further compressed in time domain after the dispersion compensation and the peak power of the pulses is increased, therefore the spectral broadening in the DF-HNLF2 is enhanced. It is noted that, as shown in Fig. 2, the DF-HNLF is designed to have low normal dispersion over a broad wavelength range, making it possible to achieve SPM based frequency comb broadening at tunable center wavelengths within C and L band. In the experiment, we have demonstrated center wavelength tunability from 1535 nm to 1564 nm for the generated broad-band frequency comb.

3. Results and Discussion

3.1 Broadband Optical Frequency Comb Generation With Flexible Central Wavelength

We first investigate the tunability of center wavelength for the generated frequency comb with 25-GHz frequency spacing. Since the DF-HNLF used in the experiment has low dispersion in a wide wavelength range, the central wavelength of the frequency comb can be tuned flexibly. By tuning the wavelength of the CW laser and center wavelength of the optical bandpass filter, the broad-band frequency comb can be generated at the center wavelengths of 1535 nm, 1550 nm and 1564 nm, respectively, as shown in Figs. 3–5. For the launched power of 30 dBm, the 30-dB bandwidths of the generated frequency combs are 125 nm, 132 nm and 132 nm for the center wavelengths of 1535 nm, 1550 nm and 1564 nm, respectively. The bandwidth of the frequency comb is slightly larger for the longer wavelength since the DF-HNLF has lower dispersion at the longer wavelength.

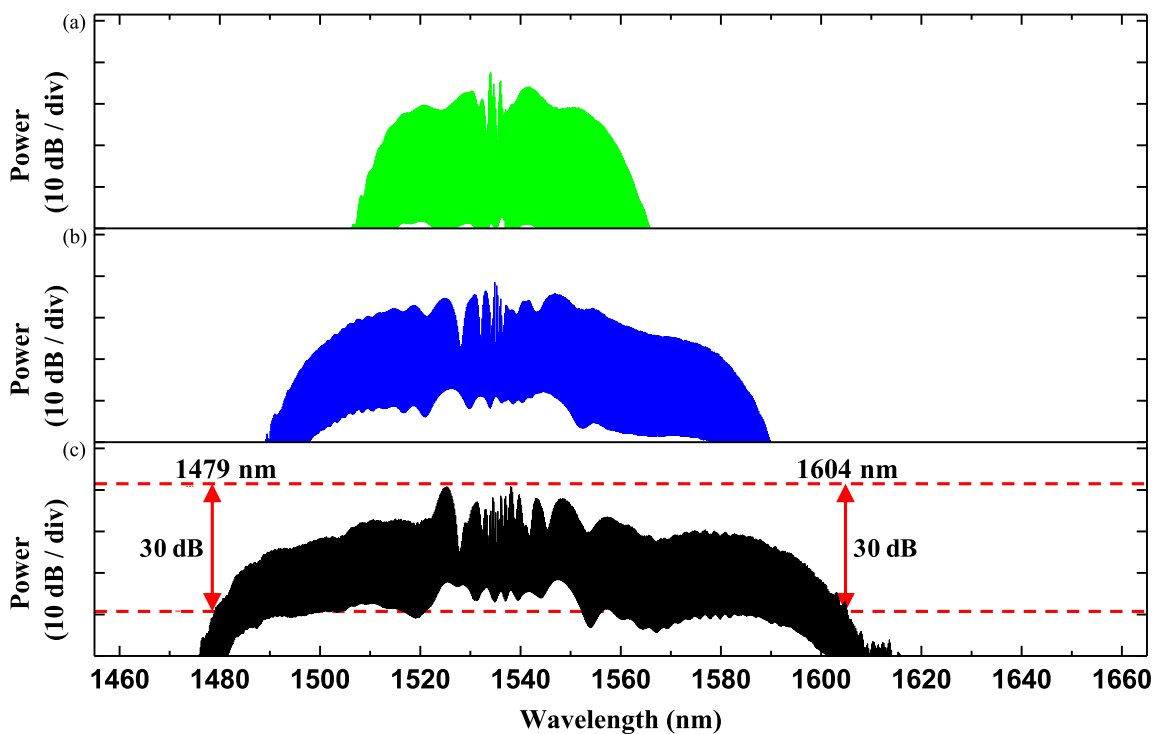


Fig. 3. Broad-band frequency comb generation with the center wavelength of 1535 nm and the frequency spacing of 25-GHz. (a) with 24 dBm launched power; (b) with 27 dBm launched power; (c) with 30 dBm launched power.

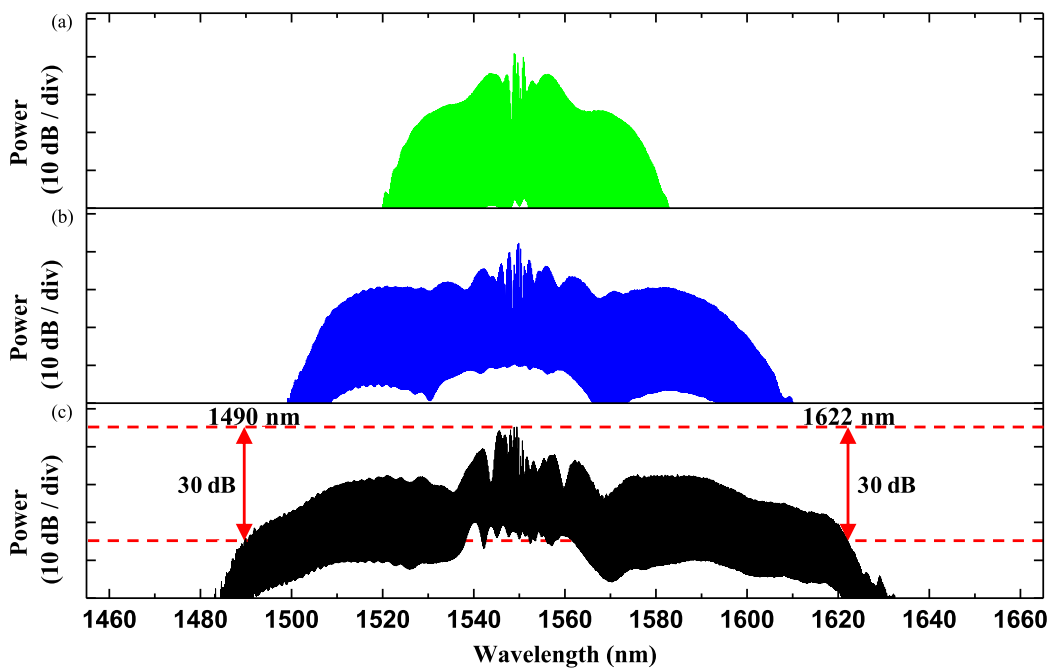


Fig. 4. Broad-band frequency comb generation with the center wavelength of 1550 nm and the frequency spacing of 25-GHz. (a) with 24 dBm launched power; (b) with 27 dBm launched power; (c) with 30 dBm launched power.

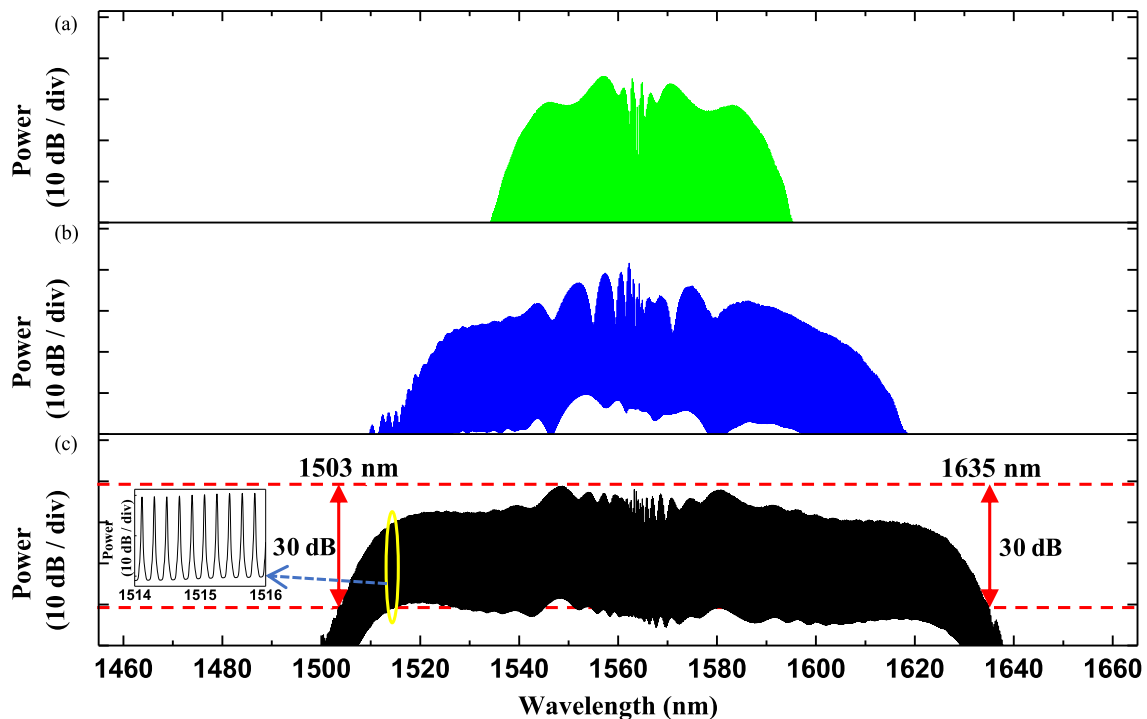


Fig. 5. Broad-band frequency comb generation with the center wavelength of 1564 nm and the frequency spacing of 25-GHz. (a) with 24 dBm launched power; (b) with 27 dBm launched power; (c) with 30 dBm launched power. Inset is the zoom-in of measured frequency comb with 30 dBm launched power.

For the 25-GHz frequency comb with 1564 nm center wavelength and 30 dBm launched power, there are totally ~ 660 comb lines within the 30-dB bandwidth, therefore the average power per comb line is ~ 1 dBm taking into account of ~ 1 dB of insertion loss of the DF-HNLFs. The linewidth of the generated frequency comb is supposed to be preserved compared to the seed laser, as expected given the correlated phase of the seed laser [21]. In addition, we also investigate the impact of the launched power on the bandwidth of frequency comb. When the launched power is higher, the bandwidth of the frequency comb becomes larger. As shown in Fig. 3, the 30-dB bandwidth of the generated frequency comb with 25-GHz spacing is 55 nm, 94 nm and 125 nm, respectively, for the launched power of 24 dBm, 27 dBm and 30 dBm.

3.2 Broadband Optical Frequency Comb Generation With Frequency Spacing

Furthermore, the tunability of frequency spacing is also investigated for the generated frequency comb. In order to tune the frequency spacing of the frequency comb from 25 GHz to 40 GHz, the driving RF signal is adjusted to 40 GHz and the driving narrow-band RF amplifier is replaced by the one with a center frequency of 40 GHz. As shown in Fig. 6, the frequency comb with 40-GHz frequency spacing is generated with center wavelengths of 1535 nm, 1550 nm and 1564 nm. For the launched power of 30 dBm, the generated frequency comb with 40-GHz frequency spacing has a 30-dB bandwidth of 155 nm, 155 nm and 164 nm at the central wavelength of 1535 nm, 1550 nm and 1564 nm, respectively. The dispersion profile of the DF-HNLF is not uniform along the fiber and there are dispersion variations over a broad wavelength range, which causes the varying spectral envelope of the generated comb.

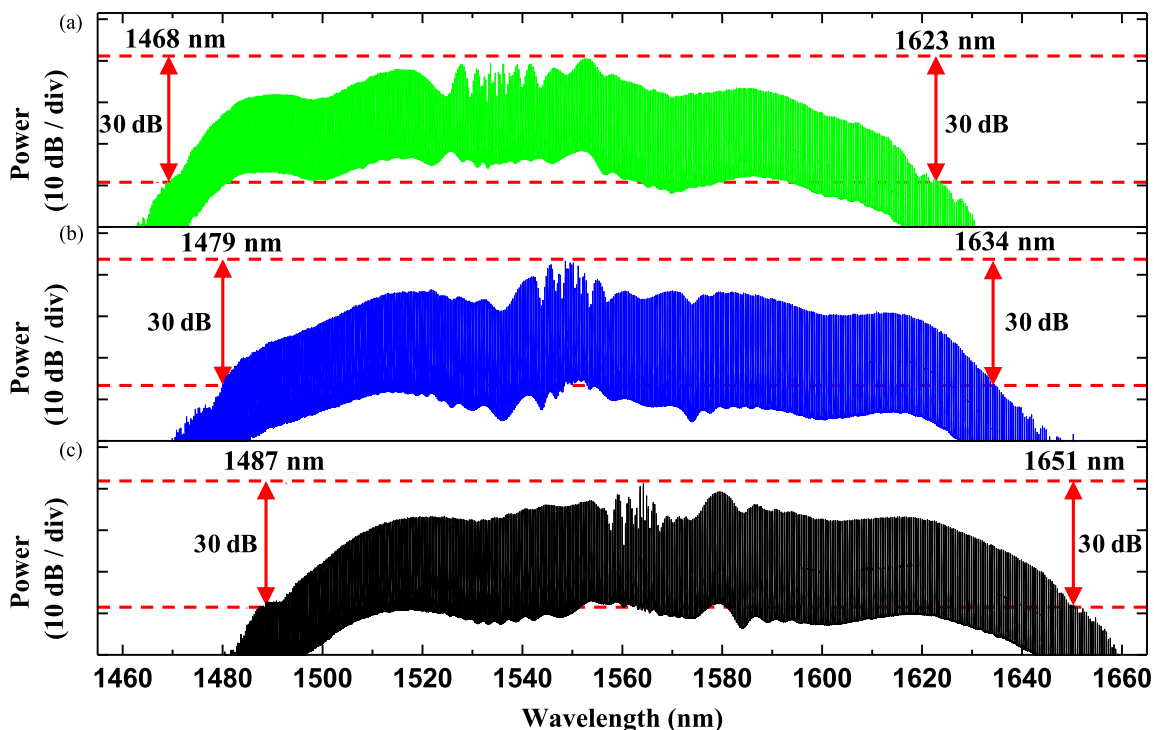


Fig. 6. Broad-band frequency comb generation with the frequency spacing of 40-GHz and 30 dBm launched power. (a) with the central wavelength of 1535 nm; (b) with the central wavelength of 1550 nm; (c) with the central wavelength of 1564 nm.

4. Conclusion

In summary, we have experimentally demonstrated a broad-band frequency comb with flexible center wavelength and frequency spacing. Broad-band frequency comb is achieved by using cascaded intensity modulator and phase modulator followed by two-stage DF-HNLFs. By adjusting the seed laser wavelength, the center wavelength of the broad-band frequency comb can be tuned, since the DF-HNLFs have a low dispersion over a broad wavelength range. By adjusting the driving RF signal, the frequency spacing the frequency comb can be adjusted. For the launched power of 30 dBm, the generated 25-GHz frequency comb has a 30-dB bandwidth of 125 nm, 132 nm and 132 nm and the 40-GHz frequency comb has a 30-dB bandwidth of 155 nm, 155 nm and 164 nm at the wavelength of 1535 nm, 1550 nm and 1564 nm, respectively.

Acknowledgment

The authors would like to thank the Centre for Excellence Silicon Photonics for Optical Communications of the Technical University of Denmark.

References

- [1] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical frequency metrology," *Nature*, vol. 416, no. 6877, pp. 233–237, 2002.
- [2] F. C. Cruz, "Optical frequency combs generated by four-wave mixing in optical fibers for astrophysical spectrometer calibration and metrology," *Opt. Express*, vol. 16, no. 17, pp. 13267–13275, 2008.
- [3] A. Cingöz *et al.*, "Direct frequency comb spectroscopy in the extreme ultraviolet," *Nature*, vol. 482, no. 7383, pp. 68–71, 2012.
- [4] S. Bennett, B. Cai, E. Burr, O. Gough, and A. J. Seeds, "1.8-THz bandwidth, zero-frequency error, tunable optical comb generator for DWDM applications," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, pp. 551–553, May 1999.

- [5] S. Jia *et al.*, "THz photonic wireless links with 16-QAM modulation in the 375-450 GHz band," *Opt. Express*, vol. 24, no. 21, pp. 23777–23783, 2016.
- [6] M. I. Afzal, K. Alameh, and Y. T. Lee, "Symmetry breaking of frequency comb in varying normal dispersion fiber ring cavity," arXiv:1610.05130, 2016.
- [7] E. Temprana, V. Ataie, B. P.-P. Kuo, E. Myslivets, N. Alic, and S. Radic, "Low-noise parametric frequency comb for continuous C-plus-L-band 16-QAM channels generation," *Opt. Express*, vol. 22, no. 6, pp. 6822–6828, 2014.
- [8] H. Hu *et al.*, "Single-source AlGaAs frequency comb transmitter for 661 Tbit/s data transmission in a 30-core Fiber," in *Proc. Int. Conf. Lasers Electro-Opt.*, 2016, Paper JTh4C.1.
- [9] P. Marin *et al.*, "Microresonator-based solitons for massively parallel coherent optical communications," *Nature*, vol. 546, no. 7657, pp. 274–279, 2017.
- [10] A. Fulop *et al.*, "Long-haul coherent transmission using a silicon nitride microresonator-based frequency comb as WDM source," in *Proc. Int. Conf. Lasers Electro-Opt.*, 2016, Paper SM4F.2.
- [11] E. Temprana *et al.*, "Overcoming Kerr-induced capacity limit in optical fiber transmission," *Science*, vol. 348, no. 6242, pp. 1445–1448, 2015.
- [12] V. Corral, R. Guzmán, C. Gordón, X. J. M. Leijtens, and G. Carpintero, "Optical frequency comb generator based on a monolithically integrated passive mode-locked ring laser with a Mach–Zehnder interferometer," *Opt. Lett.*, vol. 41, no. 9, pp. 1937–1940, 2016.
- [13] A. Bartels, D. Heinecke, and S. A. Diddams, "Passively mode-locked 10 GHz femtosecond Ti:sapphire laser," *Opt. Lett.*, vol. 33, no. 16, pp. 1905–1907, 2008.
- [14] C. He, S. Pan, R. Guo, Y. Zhao, and M. Pan, "Ultraflat optical frequency comb generated based on cascaded polarization modulators," *Opt. Lett.*, vol. 37, no. 18, pp. 3834–3836, 2012.
- [15] Y. Dou, H. Zhang, and M. Yao, "Generation of flat optical-frequency comb using cascaded intensity and phase modulators," *IEEE Photon. Technol. Lett.*, vol. 24, no. 9, pp. 727–729, May 2012.
- [16] R. Wu, V. R. Supradeepa, C. M. Long, D. E. Leaird, and A. M. Weiner, "Generation of very flat optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms," *Opt. Lett.*, vol. 35, no. 19, pp. 3234–3236, 2010.
- [17] R. Wu, V. Torres-Company, D. E. Leaird, and A. M. Weiner, "Supercontinuum-based 10-GHz flat-topped optical frequency comb generation," *Opt. Express*, vol. 21, no. 5, pp. 6045–6052, 2013.
- [18] V. Ataie, B. P.-P. Kuo, E. Myslivets, and S. Radic, "Generation of 1500-tone, 120nm-wide ultraflat frequency comb by single CW source," in *Proc. Int. Conf. Opt. Fiber Commun.*, 2013, Paper PDP5C.1.
- [19] E. Myslivets, B. P. P. Kuo, N. Alic, and S. Radic, "Generation of wideband frequency combs by continuous-wave seeding of multistage mixers with synthesized dispersion," *Opt. Express*, vol. 20, no. 3, pp. 3331–3334, 2012.
- [20] H. Hu *et al.*, "10 GHz pulse source for 640 Gbit/s OTDM based on phase modulator and self-phase modulation," *Opt. Express*, vol. 19, no. 26, pp. B343–B349, 2011.
- [21] Z. Tong, A. O. J. Wiberg, E. Myslivets, B. P. P. Kuo, N. Alic, and S. Radic, "Spectral linewidth preservation in parametric frequency combs seeded by dual pumps," *Opt. Express*, vol. 20, no. 16, pp. 17610–17619, 2012.