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Generation of 2 THz Span Optical Comb in a Tunable Fiber Ring Based Optical Frequency Comb Generator

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***Abstract*— The generation of a 2 THz span optical comb, defined within a 10 dB power envelope and consisting of 200 optical comb lines, all stronger than -20 dBm without amplification, is reported. The effective transmittance of the generator is 11.5 dB. The comb line spacing can be adjusted with a step frequency that equals an integer multiple of 12.500 MHz while maintaining the comb profile. High coherence between the comb lines is achieved, with the beat signal between the comb lines having a noise level of -92 dBc/Hz at 1 kHz offset, and phase noise of -130 dBc/Hz at 1MHz offset.**

I. INTRODUCTION

The optical frequency comb generator (OFCG) is a unique device that produces multiple, equally spaced optical comb lines in the spectral domain. Its capability for locking the comb lines to a stabilized reference laser, and the high coherence between comb lines has attracted much interest, such as in optical frequency measurements, radio over fiber, ultra-dense wavelength-division-multiplexing systems, phase array antennas, and millimeter-wave to THz LO generation and imaging [1-4].

While the bulk-optics OFCG [5] is capable of producing optical combs with an equilateral triangle spectral profile and with the comb span up to a few THz, the low transmittance in such a device requires a strong reference laser and results in a very low power in the individual comb lines. The transmittance, measured by the total optical power of the comb against the reference optical power, can be improved by a coupled cavity configuration, resulting in an improvement from 0.3% to 16 % [6]. The limited cavity length in such devices also results in a very coarse tunability, i.e. a few GHz in the comb line spacing, unless the cavity length is continuously adjusted to match the resonance while the tuning is performed.

The fiber ring based OFCG [7] overcomes these difficulties. Because of the gain within the loop, the transmittance can be improved to over 1. Furthermore, the relatively long cavity results in flexibility in the comb line spacing with a resolution of few MHz [2, 4]. The problems with this type of OFCG are the difficulties in the management of the comb line powers, in the maintaining of the optical resonance, and in the maintaining of stability over time against ambient temperature changes and wavelengths drift of the reference laser. Previous work has generated an optical comb covering up to 1.8 THz, and containing about 100 comb lines in a 40 dB power envelope with reference to a linewidth broadened external cavity laser [8]. In this paper, we report an OFCG that produces tunable optical combs with much flatter profile in a wider span, while the system is referenced to a narrow linewidth laser, and achieves a transmittance over 10.

II. EXPERIMENTAL SETUP

Fig. 1 illustrates the setup of the fiber ring based OFCG. The system consists mainly of a fiber loop, including an Erbium Doped Fiber Amplifier (EDFA) and an optical phase modulator. A 16 nm thin film filter (centered at 1551 nm) is

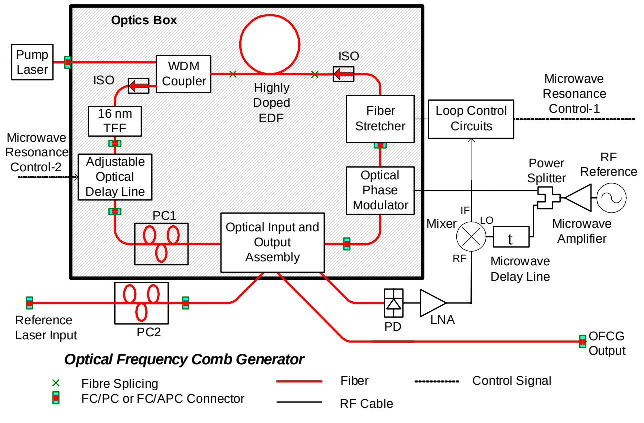

Figure 1. Fibre ring based optical frequency comb generator with error correction loop

ISO: optical isolator; LNA: Low Noise Amplifier; PD: Photodetector; PC: Polarization controller; TFT: Thin Film Filter

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incorporated at the output of the EDFA to remove the gain peak around 1530 nm. A polarization controller is employed to match the polarization of the circulating light to the principal axis of the optical phase modulator. Optical resonance error is resolved by the homodyne detection of the amplitude of the fundamental beat signal of the optical comb. This error signal is processed and fed into a low polarization change fiber stretcher embedded inside the loop, as shown in Fig.1. An in-house designed manually adjustable optical delay line which features low polarization change over its range is inserted into the loop to allow fine tuning of the cavity length so that the free spectral range (FSR) of the ring is 12.500 MHz.

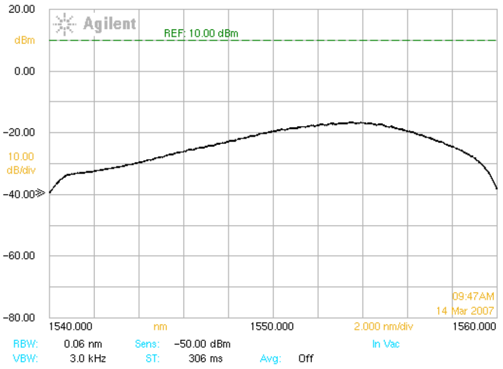


Figure 2. The system operating as a mode locked laser when RF modulation is applied

III. EXPERIMENTAL RESULTS

A. Optical Comb Generation

When the EDFA is pumped to overcome the insertion loss, the ring cavity begins to oscillate, acting as a multimode single- or multi-wavelength fiber laser with a mode spacing of 12.5 MHz. The oscillation peak(s) can be at any wavelength since the gain profile is very flat. Mode jumps occur from time to time, due to small disturbances and ambient temperature changes.

When an RF reference, which has a frequency that equals an integer multiple of the 12.5 MHz FSR is applied, the laser becomes mode locked. Fig. 2 shows the mode locked optical spectrum when a 10 GHz modulation is applied. Depending on the exact microwave resonance condition and the polarization settings, the mode locked spectrum may contain one or a multiple number of peaks. Due to the fact that the cavity lacks mode selection of the densely populated optical resonance modes, multiple sets of the locked optical modes will be supported simultaneously, even though the optical spectrum may appear to have just one peak. These sets of modes are interleaved at a frequency that equals the FSR of the cavity, i.e. 12.5 MHz. There is no particular set of optical modes that can stably dominate the spectrum over time. The optical spectrum can appear smooth for each of the wavelength peaks as the OSA can not resolve the closely spaced optical modes. This indicates that this type of operation is not the most suitable for use as an optical comb generator.

The injection of an optical reference light reinforces one or several sets of the locked modes. As a result, they will dominate the optical spectrum and suppress the remaining modes by lowering the round-trip gain through the saturation of the optical amplifier. The dominance of the sets of the modes will remain until the optical phase resonance condition is lost due to drifts of either the cavity length or the reference laser frequency. In the case of a reference laser with linewidth much broader than the FSR of the OFCG, there will be

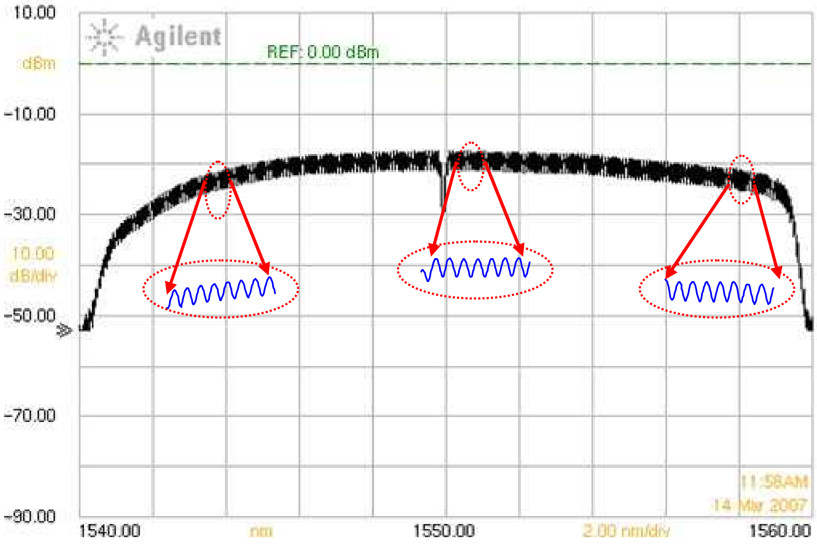


Figure 3. Optical comb with over 2 THz span within 10 dB power envelope

Inserted are the details of the optical spectra at different wavelengths. The comb spacing is 10 GHz and there are more than 200 comb lines within a 10 dB power envelope. The spectrum is measured after a 3 dB optical coupler with an insertion loss of 4 dB.

multiple sets of the optical modes being supported simultaneously. In this case [8], the OFCG operates as a multi-mode injection locked mode-locked laser. The drifts will cause slight power redistribution among the neighboring sets of modes, but the optical resonance condition holds all of the time. Limited by the optical spectrum resolution, a comb-like optical spectrum can be maintained, with each of the optical comb “lines” containing a number of cavity modes, suffering small fluctuations due to power redistribution between them.

However, in the case of a narrow linewidth reference laser, the drifts will cause the optical spectrum to change dramatically. This is because the loss of the optical resonance of the only set of dominant modes will encourage free-running oscillation at other frequencies to occur. Furthermore, the long cavity results in much more densely populated cavity modes, making the cavity more sensitive to the wavelength drift of the reference laser and to the ambient temperature drift. Therefore, an optical resonance error correction circuit has to be employed in this case to track any drifting.

When such an error correction loop is switched on, an ultra flat comb can be produced, as shown in Fig.3. In this measurement, the OFCG is locked to an optical reference at 1550 nm with an optical power level of 0.5 mW. A 10.000 000 GHz RF reference with a power level of 6.3 dBm is applied as the microwave reference, locking to the 800th harmonic of the cavity modes. With a 510 mA EDFA pump current, the total OFCG output power reaches 8.5 dBm, achieving a transmittance of 11.5 dB. The optical power is distributed into more than 200 optical comb lines in a wavelength span exceeding 16 nm. Within the 3 dB power envelope, there are more than 100 comb lines in a span exceeding one THz. Fig.4 depicts the close-in view of the optical comb in a span from 1550 nm to 1556 nm, showing a power slope of 2 dB. Cleary all the power is rather focused on a band of 2 THz, with similar power levels among the comb lines. The sharp roll off of the optical comb at the edges of the comb is due to the bandwidth of the thin film filter. This filter not only contributes to the concentration of the power into the central 2THz band, but also allows the OFCG to be pumped harder, achieving a flatter profile by eliminating the gain peak. The minimum comb line power within the 2 THz span is -20 dBm. There is no drop out of any particular comb lines (no missing lines), except at the reference wavelength, which in many applications it is desired to remove or suppress [10] anyway. A slight imbalance in longer wavelength and shorter wavelength sides of the optical comb can be attributed to the four wave mixing and a small gain slope in the round-trip transmittance. It is observed that the OFCG stays locked to the same optical mode stably over hours in the laboratory once the locking is achieved, maintaining the profile of the comb until the range of the fiber stretcher runs out.

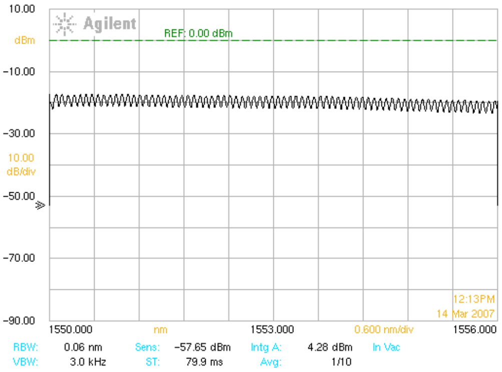
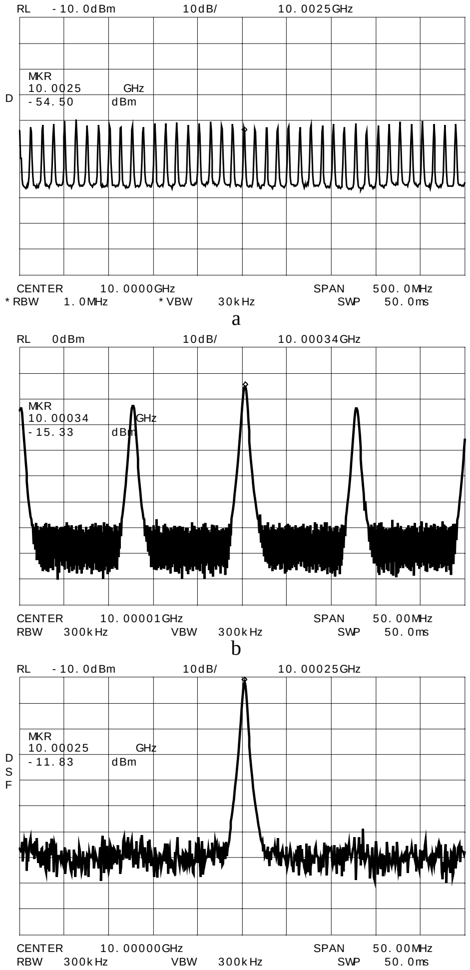


Figure 4. Flatness of the optical comb.

The comb lines have similar power level over a range of 6 nm and there is no drop out in the comb lines.

It has also been verified that the same OFCG can be locked to different reference lasers at different wavelengths. For instance by replacing the 1550 nm laser by an 1556 nm laser, an optical comb centered at 1556.2 nm is generated, with the comb being cut off around 1559 nm due to the filter.



a

b

c

Figure 5 RF spectra of the beat signal from the system under different operational conditions

a: as a free-running laser without RF and optical reference; b: as a mode locked laser, (the corresponding optical spectrum is in Fig. 2); c: as an optical comb generator with an optical reference light level of -3 dBm (the corresponding optical spectrum is in Fig. 3)

Moreover, when the comb line spacing is being adjusted, the comb profile will be roughly maintained [9]. Comb line spacing adjustment from 6 GHz to 12 GHz has been performed, without the need for any fine tuning to the system. The resolution of the supported comb line spacing frequency is 12.5 MHz, which is fixed once the comb is locked. The time required for the comb line adjustment is less than 1 second. Stable operation over hours can be achieved while the comb line spacing is being adjusted.

B. Coherence between the Comb Lines

The coherence of the comb line is demonstrated in Fig. 5. For comparison, the spectra of the beat signal from the system running as a free running laser (a), as a mode locked (b) and as the comb generator (c) are all presented. Clearly, while the mode locked operation can suppress some of the cavity modes, strong residual modes still exist in the spectrum of the beat signal due to the beating between the different sets of the locked modes. The injection of the reference light in the OFCG effectively removes the residual cavity modes, and leaves only a clean beat signal at the modulation frequency. Beating one of the comb line to an independent fiber laser operating 6 nm from the reference laser wavelength has been carried out, confirming that the comb lines are single mode and have a linewidth of less than 10 kHz each, similar to that of the reference laser.

Fig. 6 shows the close-in view of the fundamental beat signal. The signal carries a 1/f noise, with a noise level of -92 dBc/Hz at 1 kHz offset. The corresponding phase noise measurement shows that the phase noise is about -130 dBc/Hz at an offset of 10 MHz.

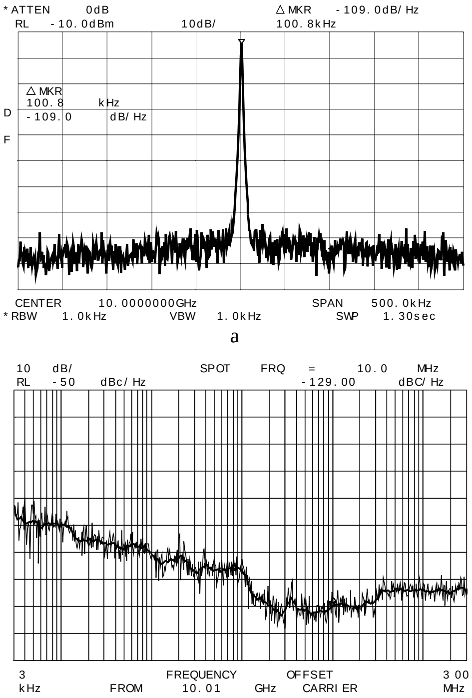


Figure 6 Close-in view of the typtical fundamental beat signal (a) and its phase noise (b)

IV. CONCLUSION

In this paper, a very flat optical comb with a span of 2 THz is demonstrated for a fiber ring based optical frequency comb generator. The system is capable of locking to a narrow linewidth reference laser. The demonstrated system has a transmittance of 11.5 dB and therefore requires a power level of only 0.5 mW from the optical reference, producing relatively strong comb lines of greater than -20 dBm per comb line across the 2 THz span. Stable operation is achieved over hours and the comb line spacing can be switched with a resolution of 12.5 MHz over an octave. The generated optical comb has suppressed residual cavity modes, resulting in a single mode in each of the comb lines. A phase noise of -130 dBc/Hz is achieved at 1 MHz offset, and a 1/f noise with a level of -92 dBc/Hz is achieved at 1 kHz offset.

REFERENCES

[1] T. Udem, J. Reichert, R. Holzwarth, and T. W.Hänsch, “Absolute optical frequency measurement of the cesium D1 line with a mode-locked laser,” *Phys. Rev. Lett.*, vol. 82, pp. 3568-3571, 1999

[2] P. Shen, P. A. Davies, W. P. Shillue, L. R D’Addario, J. M. Payne, “Millimetre-wave generation using an optical comb generator with optical phase-locked loops,” *IEEE Intl. Topical Meeting on Microwave Photonic*s, *MWP2002*, pp. 101-104, Awaji, Japan, 2002

[3] L. R. Brothers, N. C. Wong, “Optical frequency comb generation for terahertz difference-frequency measurements,” *Proc. SPIE Laser Frequency Stabilization and Noise Reduction*, vol. 2378, pp. 222-229, 1995

[4] O. P. Gough. C. F. C. Silva, S. Bennett, A. J. Seeds, “Zero frequency error DWDM channel synthesis using optical injection-locked comb line selection,” *Electron. Lett.*, vol. 35, pp. 2050-2052, 1999

[5] M. Kourogi, K. Nakagawa and M. Ohstu, “Wide-span optical frequency comb generator for accurate optical frequency difference measurement,” *IEEE J. Quantum Electron.*, vol. 29, pp. 2693-2701, 1993

[6] M. Kourogi, T. Enami, and M. Ohtsu, “A coupled-cavity monolithic optical frequency comb generator,” *IEEE Photonic Technol. Lett.*, vol. 8, pp. 1698-1700, 1996

[7] K. P. Ho and J. M. Kahn, “Optical frequency comb generator using phase modulation in amplified circulating loop,” *IEEE Photonic Technol. Lett.*, vol. 5, pp. 721-725, 1993

[8] 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 Photonic Technol. Lett.*, vol. 11, pp. 551-553, 1999

[9] P. Shen, N. J. Gomes, P. A. Davies, P. G. Huggard and B.N. Ellison, “Analysis and demonstration of a fast tunable fiber-ring based optical frequency comb generator”, Accepted by *J. Lightw. Technol.*

[10] S. Fukushima, C. F. C. Silva, Y. Muramoto, and A. J. Seeds, “Optoelectronic millimetre-wave synthesis using an optical frequency comb generator, optically injection locked lasers, and a unitravelling-carrier photodiode,” *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3044-3051, 2003