Analysis and Demonstration of a Fast Tunable Fiber-ring Based Optical Frequency Comb Generator

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***Abstract*—Fiber ring based optical frequency comb generators are analyzed in order to understand their behavior and limitations. A numerical frequency domain model is described for studying dispersion and other phase mismatch causing effects in the fiber ring cavity, as well as for predicting the spectral and temporal evolution of the comb in time. The results from this analysis are verified with experimental measurements. A flat optical comb, with a THz span within a 6 dB power envelope, and containing 100 comb lines, with a suppressed central comb line, is demonstrated. The comb shows excellent coherence dependent on the phase noise from the RF synthesizer that drives the comb generator. Improvement in the error correction loop also enables the comb spacing to be set at precise 12.5 MHz intervals without having to adjust the system. Fast frequency switching of the comb line spacing is demonstrated for the first time. The comb line spacing can be switched to any operation frequency with a resolution of 12.5 MHz between 6 GHz and 12.5 GHz, limited only by the microwave circuit used. The switching time is less than 1 second and the spectral profile of the comb is maintained.**

***Index Terms*—Optical frequency comb generator, frequency switching, fiber ring, phase noise**

I. Introduction

OPTICAL frequency comb generators (OFCGs) are of significant interest for a number of applications, ranging from frequency references for WDM and optical FDM systems, to terahertz signal generators and optical frequency measurement [1]. Many methods have been proposed for OFCG implementation, such as active mode locking [2], pulse compression through effects such as four-wave mixing and self-phase modulation [3], and resonator types such as phase modulation within monolithic Fabry-Perot cavities [1],[4],[5]. In [6], a coupled-cavity monolithic optical frequency comb generator is used together with self-phase modulation, to achieve a 50 THz span. However, the monolithic optical frequency comb generator requires very large RF and optical power. Its power transmittance, described by the output comb power compared to the input reference power is low, making it inconvenient for many applications. Meanwhile, the fiber ring based OFCG [7]-[10] provides an alternative to these bulk optics systems, is more focused on telecommunications wavelengths, and provides features such as low drive power and high efficiency.

The fiber ring based OFCG was first proposed by Ho and Kahn [7] based on re-enforced phase modulation within a fiber loop, in which all components used were readily available telecommunication components. Unlike the conventional, monolithic Fabry-Perot cavity based OFCG, the finesse of the fiber ring [11] is not determined by the coupling efficiency of the input/output coupler only. It is also related to the internal gain. Therefore, a large fraction of the optical power can be transferred to high order sidebands, enabling a wide comb to be produced. A theoretical analysis of the fiber ring OFCG based on a time domain model was also given. Bennett et al. presented such a ring based OFCG, achieving 1.8 THz comb span, and containing 103 lines within a power envelope of 40 dB [8].

The length of the fiber ring leads to a narrow free spectral range, of typically a few MHz. This makes stable operation very difficult unless multiple cavity modes per comb line are allowed to stabilize the comb [8]. At the University of Kent, a fiber ring based OFCG has been developed [9] in which an error correction circuit enables the stable operation of the OFCG with narrow line width lasers, locked or unlocked to a wavelength reference such as gas cell. With each of the comb lines containing only one cavity mode, the residual cavity mode noise is greatly suppressed. Millimeter wave generation has been demonstrated by using this OFCG and a phase locked laser [9].

It is very desirable for the OFCG to be flexible in its operational frequency. While resonant type OFCGs can work with different reference optical frequencies, the adjustment of the comb line spacing is limited by the length of the cavity. The

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monolithic Fabry-Perot OFCG operates at its fundamental cavity mode spacing or the immediately higher order modes, potentially enabling a frequency adjustment at a resolution of no finer than a few GHz. Adjustment with finer frequency resolution needs to involve the change of the length of the cavity, and this leads to difficulties in precisely matching the cavity to the new operational frequency and very long switching times.

Owing to its long cavity, the fiber ring based OFCG can potentially support a resolution of the comb line spacing at MHz level. It operates at a much high order of the cavity mode frequencies, enabling hundreds to thousands of tuning steps, without adjustment of the cavity length. However, such tuning has only previously been carried out over a limited bandwidth of a few tens of MHz, due to problems in maintaining the stability of the comb. In this paper, we present the theory of the fiber ring based OFCG based on a frequency domain analysis. This allows us look to into the spectral evolution of the comb. From the analysis, it is clear that the power efficiency in the generation can be high allowing the use of reference lasers of sub-milliwatt level power, while generating strong comb lines. The frequency spacing of the comb can be adjusted and a stabilized comb can be built up within a few milliseconds when optical and microwave resonances are maintained within the main cavity and the error correction loop. In the later section of the paper, we present an OFCG which produces wide-span optical comb, a THz wide in a 6 dB envelope. Its power efficiency is very high, with the total power in the comb lines 11 dB above the reference lightwave power level. For the first time, we are able to demonstrate the fast frequency switching in the comb line spacing, across the entire operational frequency band from 6 GHz to 12.5 GHz, limited by the microwave circuit bandwidth, in frequency steps of precisely 12.5 MHz.

II. OFCG Modeling

The fiber ring based OFCG has been studied through the general multi-pass time domain model [7]. In fact, the operation can be better understood by treating the ring cavity as a scanning fiber ring resonator with high finesse. The internal phase modulation changes the ring length and thus causes the fringes to move across the wavelength. This produces peaks of transmission and hence a wide span of the optical comb. The two analyses yield the same results as they are both based on time domain analysis, describing the output through a pulse train. This is generally sufficient for predicting the performance of an ideal OFCG. However, this time domain model is only suitable for a comb spectrum after the comb has been built up, and can not include effects such as the fiber dispersion, non-flat gain profiles and the RF frequency mismatching.

For a fiber ring based OFCG, the cavity length can reach from a few meters to tens of meters. Such a long cavity reduces the FSR but produces more chromatic dispersion. The existence of chromatic dispersion will lead to the cavity resonance modes no longer being evenly spaced. As a result, the frequencies of the phase modulation sidebands may not be coincident with the cavity modes, and hence may not be supported by the cavity resonance. Thus, a numerical model has been developed to allow the analysis of the OCFG in the presence of dispersion. The same model also makes it possible to incorporate the wavelength dependent gain curve of the optical amplifier and other wavelength dependant components, and to analyse the RF detuning effect.

The numerical model presented here is based on calculating the optical spectrum while the light is circulating inside the cavity. It starts with the spectrum of the reference laser, which can be treated as a single frequency lightwave due to the narrow linewidth of the reference light. As the lightwave propagates inside the cavity, the effect of each of the optical components is accounted for: the spectrum is changed due to modulation, propagation delay, dispersion and the nonlinear response of the components. After a round-trip, the lightwave interferes with the reinforcing reference lightwave at the optical coupler. The resulting lightwave will continue circulating inside the loop and the optical spectrum will evolve until eventually equilibrium will be reached and a stable output attained.

To implement this model, the spectra of the comb lines are represented in their complex amplitude. Ignoring the temporal instability of the reference lightwave, these comb lines always take frequencies defined by the frequencies of the modulation sidebands. The effect of the optical phase modulator on a lightwave is considered as

$$\vec{E}_o(t) = \vec{E}_i(t) e^{-j\beta \sin(\omega_m t)} \tag{1}$$

where the $\vec{E}_i(t)$ is the complex amplitude time function of the input lightwave, $\vec{E}_o(t)$ is the output from the phase modulator, β is the modulation frequency, ω_m is the angular modulation frequency and t is time.

When the incident light is no longer a single frequency lightwave, the relation shown in (1) still holds. Clearly the resulting lightwave is a product of the time function of the incident lightwave and a phase varying term $e^{-j\beta \sin(\omega_m t)}$. The Fourier component $\vec{M}$ of the phase varying term at the angular frequency $n\omega_m$ is given by

$$\vec{M}(n\omega_m) = J_{-n}(\beta) \tag{2}$$

Knowing the Fourier transform of the incident lightwave, the spectrum of the resulting lightwave $\vec{E}_o(\omega)$ can then be calculated by the convolution theorem,

$$\vec{E}_o(\omega) = \vec{E}_i(\omega) * \vec{M}(\omega) \tag{3}$$

where $\vec{E}_i(\omega)$ is the spectrum of the input light.

Overall, the insertion loss of the passive components and the gain of the optical amplifier can be treated together. A round-trip transmittance function is used to describe these effects. In each round-trip, the spectrum is multiplied by the round-trip transmittance. If the width of the comb is less than the bandwidth of the optical gain medium and other passive optical components, the round-trip transmittance should have a magnitude close to unity for all wavelengths; this should be the case unless the reference laser is operated too close to the edge of the passband of the OFCG.

Apart from the phase shift arising from the optical amplifier, dispersion exists in the optical fiber. It is better to treat the two dispersion effects together. In the case of a non-dispersive cavity, the propagation of the lightwave in the fiber is characterized by its intrinsic propagation delay and fiber loss. The group velocity v_g, which describes the propagation velocity of the pulse envelope, is equal to the phase velocity v_p. When dispersion and nonlinearity of the fiber is taken into consideration, the propagation of an optical pulse can be described by the generalized nonlinear Schrödinger equation (GNLSE) [12]. This takes into account the fiber losses, higher-order chromatic dispersion and nonlinear effects. The GNLSE is a partial differential equation, whose order depends on the nonlinear and dispersion effects considered. Under the slowly varying envelope approximation, the complex amplitude of the electric field in a single mode optical fiber is described by

$$\frac{\partial A}{\partial z} = -\frac{j}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^2} - \frac{\alpha}{2}A + j\gamma|A|^2 A \qquad (4)$$

where $A=A(z,t)$ is the complex amplitude of the electric field, z is the distance along the fiber length, and t is the time measured in a referential frame moving at the group velocity v_g of the optical pulse. β_2, β_3 are the second- and third-order dispersion parameters, respectively; α is the linear loss coefficient, and γ describes the nonlinear effects. In this case, the intrinsic propagation delay is not accounted in the GNLSE and has to be modeled separately though a phase-delay term.

The nonlinear effect of the fiber depends on the pulse shape as well as the power of the pulse. Operating the OFCG at different power levels will result in different output due to the nonlinearity of the fiber, and the saturation of the optical amplifier. This makes the analysis of the OFCG more complex. Thus, here we concentrate on the effect of chromatic dispersion on the output of the OFCG. By assuming that the peak power is low inside the cavity, one can simplify the GNLSE by just using its linear portion:

$$\frac{\partial A}{\partial z} = -\frac{j}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial t^2} \qquad (5)$$

Given that the fiber loss is already modeled by the round-trip transmission function, the loss in the GNLSE is assumed to be zero, and ignored.

Practically, the dispersion of single mode fiber is characterized by the first order dispersion parameter D_λ, which includes the contributions from material, waveguide and profile dispersion, and the dispersion slope S. These parameters are actually the first order and second order of the derivation of the group delay $\tau_g = 1/v_g$ with respect to the vacuum wavelength λ. For standard single mode fiber, the values are approximately 17 ps/(nm·km) and 0.068 ps/(nm·km^2), respectively. The parameters β_2 and β_3 are linked to D_λ and S by

$$\beta_2 = -\frac{D\lambda^2}{\omega_0} \qquad (6)$$

$$\beta_3 = \frac{\lambda^3}{\omega_0^{\ 2}}(D + \lambda\frac{dD}{d\lambda}) \qquad (7)$$

The fiber ring loop contains different types of fiber and

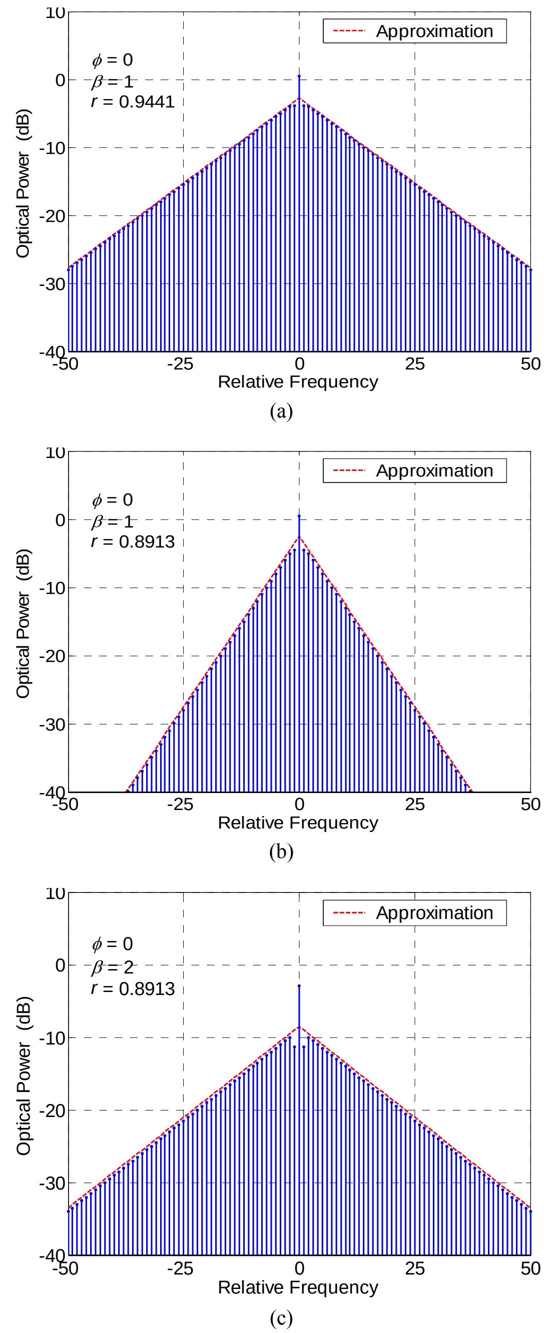
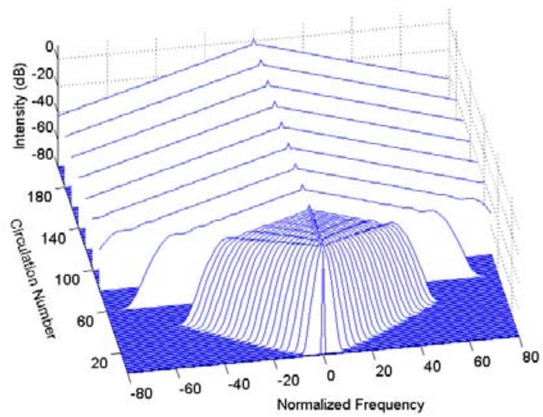


Fig. 1 Optical spectrum generated by the OFCG under different conditions

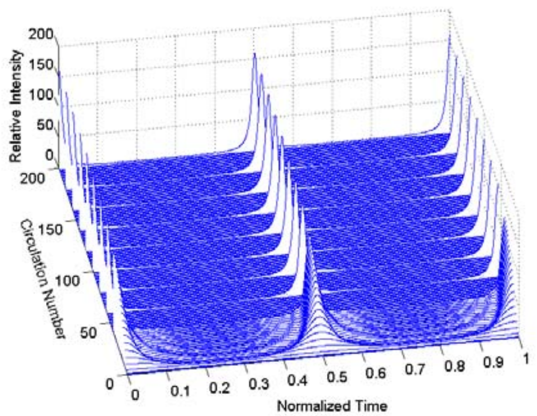
materials. It is difficult to distinguish the dispersion caused by the individual components, of which the values are unspecified. Therefore we are approximating the overall chromatic dispersion by a uniform slope that equals to the standard signal mode fiber with a effective dispersive length of L.

III. OFCG Theoretical Performance

When the model is run with a round-trip phase error of φ=0, indicating a perfect optical resonance condition at the reference wavelength, the slope in the comb shape is determined by the modulation depth and the finesse of the cavity. Fig. 1.a shows a typical comb. Fig. 1.b and 1.c demonstrate how the output spectrum will change when the round-trip gain r is decreased,



(a)



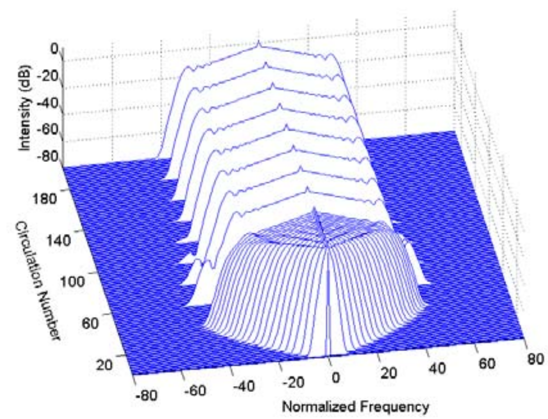
(b)

Fig. 2 The spectral evolution and pulse train evolution in a non-dispersive cavity. The simulation parameters are $\varphi = 0$, $r = 0.9441$ and $\beta = 1$
(a) is the spectral evolution (b) is the temporal evolution

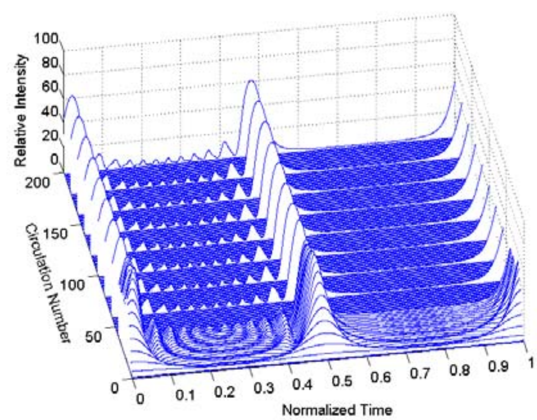
and the modulation depth β increased, respectively.

The successful wide comb-span operation of the OFCG requires both the optical resonance and microwave resonance conditions to be held for all comb line frequencies. In Fig. 2, the spectral (a) and the temporal (b) evolution of the output of the OFCG are shown, starting from the time when the reference light is just injected into the cavity. With no dispersion in the ring, it can be seen that the spectrum spreads gradually and continually in time. On the other hand, the pulse can be seen growing and narrowing as the number of passes of the lightwave through the cavity increases. However, after the first few tens of passes, further narrowing of the pulses is limited. This is because most of the power is concentrated in the lower order comb lines and these comb lines settle quickly. Due to the special phase relationship in the comb, the pulse train does not attain a very high peak power.

In the presence of dispersion in the ring, the comb builds up in a similar way as shown in Fig. 3. The comb width can be limited by dispersion and other phase mismatching conditions. This was first reported by [13] for a Fabry-Perot cavity based OFCG. For a fiber ring based OFGC, the dispersion inside the fiber is greater, and the fiber length is long. Therefore, the comb width can be limited. At the frequencies where the phase difference of an individual comb line is less than the maximum phase deviation of the modulator, the power of that comb line is effectively preserved. Within the maximum phase deviation limitation, the comb will spread more or less as in the case without dispersion. As the comb spreads further from the central region, the relative phase difference of the higher order lines will be greater than the maximum phase deviation of the



(a)



(b)

Fig. 3 The spectral evolution and pulse train evolution in a dispersive cavity. The simulation parameters are $\varphi = 0$, $r = 0.9441$and $\beta = 1.0$. Fiber length is 15 m and modulation frequency 12.5 GHz.
(a) and (b) show the spectral and temporal evolution respectively

modulator. The round-trip optical phase matching condition will not be fulfilled for these lines. As a result, these comb lines will not be supported, and their power will be sharply reduced. The span of the comb in the presence of dispersion is not affected by the modulation frequency. With a higher modulation frequency, fewer comb lines will be generated within the same comb profile. Increasing the modulation depth or reducing the chromatic dispersion in the ring are the best ways of improving the span of a dispersion limited comb.

Fig. 2 and Fig. 3 also show that the comb will be built up in just a few hundred passes, when the optical phase resonance condition holds. The build up time is thus within a millisecond. Applying a disturbance to a stable system also shows that the comb returns to a stable state in just a few milliseconds, in the worst case. This also shows that the adjustment of the modulation frequency will only cause an absence/distortion of the error detection signal for a very short period of time. As long as the fiber stretcher can be held at its original position for that period of time, the OFCG will be kept close to its original optical resonance condition. The fiber ring is not likely to pick up a micrometer of effective length change within a millisecond, therefore the optical resonance conditions will hold. Providing the OFCG was locked before the frequency switching, and the frequency is adjusted to another that is supported by the ring cavity, the OFCG will re-start with a phase matching condition and is easily locked again to the reference wavelength by the same cavity mode as before. That means the length of the cavity does not change, and this allows the comb shape to be maintained once the frequency is switched back.

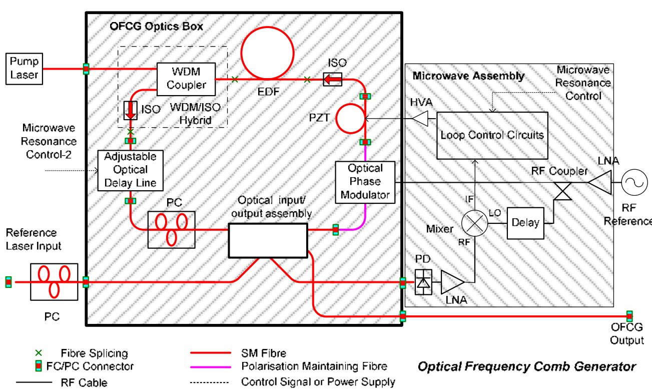


Fig. 4 Schematic diagram of the OFCG
EDF: Erbium Doped Fiber, ISO: Optical Isolator,
PC: Polarization Controller, LNA: Low Noise Amplifier
PD: Photodetector, PZT: Piezo Electric Transducer, HVA: High Voltage Amplifier

To allow frequency switching across a wide frequency range, it is also important that the error detection remains efficient over the required bandwidth. Therefore, a phase matching in the LO and RF port of the homodyne detection in the error detection circuit must be roughly maintained across the whole frequency band, as shown in Fig. 4. A RF delay-line/phase shifter is adopted to do this. One can take the advantage of the fact that the microwave resonance holds precisely in the fiber ring cavity, thus allowing a negative propagation delay concept to be used. The signal transmission from the phase modulator to the output coupler in the ring cavity can be treated as a negative path length in the opposite direction. In this approach, only short lengths of fiber and electrical cables are involved in the matching and the delays can be matched over a wider bandwidth.

IV. Experimental Results

A compact OFCG has been implemented in-house using standard telecommunications components. The ring length is fabricated precisely so that the cavity mode spacing is 12.50 MHz. Due to a lack of thermal control of the unit in its present form, this ring length, and hence the cavity mode spacing suffers thermal drift. When operation at a precise frequency is preferred, adjustment prior to operation can be made. Simple electrical tuning by adjusting the initial offset of the fiber stretcher allows an operational temperature range of 2 °C, and mechanical tuning, with an in-house manually adjustable low polarization change optical delay line, can allow a further 5 °C. Once the OFCG is on, it will lock itself automatically, and remain in lock until the fiber stretcher runs out of range. In our uncontrolled laboratory environment, this usually enables stable operation for at least several hours once the OFCG has warmed up.

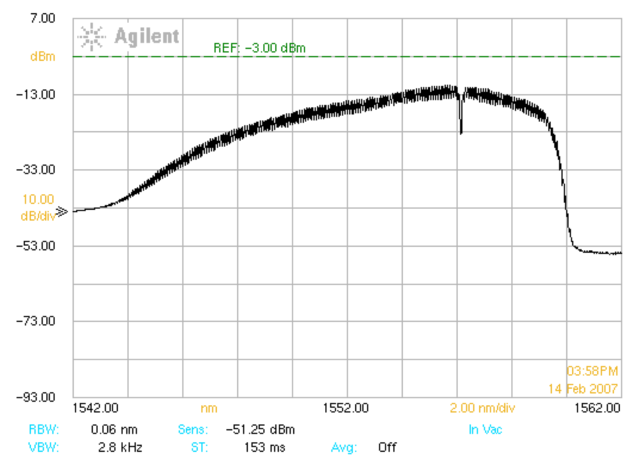


Fig. 5 Typical optical comb generated by a 10 GHz modulation and a -3 dBm optical reference lightwave signal. The 3dB and 6dB comb width are 5nm (62 line), 8 nm (100line) respectively. The sharp roll off at 1559 nm is caused by the internal amplifier gain profile, which contains a 16nm wide filter with cutoff at this wavelength

A typical output spectrum is shown in Fig. 5. This was obtained with a 10 GHz RF reference with a power level of 6 dBm, and a -3 dBm optical input at 1556.21 nm. Overall, without external amplification, the comb has a total power of 8 dBm, 11 dB higher than the reference input. The imbalance of the comb spectrum between short wavelength and long wavelength sides is due to the internal optical amplifier's cut off at 1559 nm, which means that the reference laser is operating near the edge of the OFCG passband. Within a 20 dB power envelope the comb extends over 10 nm to the short wavelength side. As the long wavelength side is limited by the particular optical amplifier and filter used in this case, this indicates that 20 nm comb width within a 20 dB power

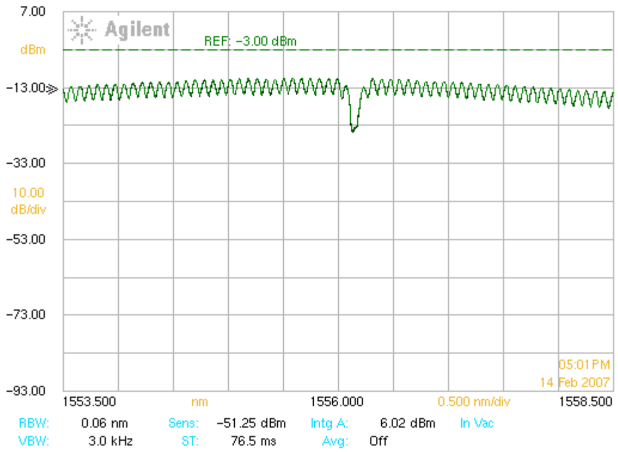


Fig. 6 Overlaid OFCG optical spectra recorded one hour apart. The OFCG is modulated at 12 GHz

envelope is possible with a wider optical filter. Within a 6 dB power envelope, the comb contains 100 lines in a span of 1 THz, with the lowest comb line power exceeding -17dBm, 2% of the reference power. The central region of the comb is very flat, as it is little affected by the passband profile of the optical amplifier. A 3 dB comb width of 6 nm is found. Compared to previous works, this is a very flat comb; in [8] the comb width is measured as 1.8 THz (with 103 lines) but in a 40 dB power envelope. Evidently, the lack of a strong comb line at the central reference wavelength is another unique feature of the OFCG. The disappearance of a strong reference wavelength is preferred in the single mode fiber-ring based OFCG, as such strong power at this wavelength can cause difficulties in selecting other comb lines [10]. Furthermore, such a strong central comb line represents an unwanted interference, which makes the comb unstable in power, spectrum and polarization. An improved dual coupler design combined with a relatively high modulation depth and a very high finesse in the ring cavity results in the suppression of the central comb line. The details of this configuration will be published in a following paper.

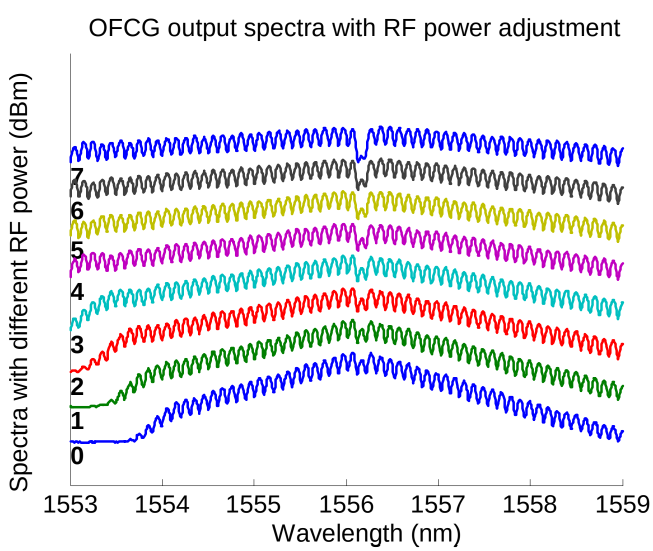


Fig. 7 OFCG optical spectra for increasing RF modulation power. The comb spacing is 12.5 GHz

Once locked, the comb shows a high degree of stability. Fig. 6 shows an overlay of the central region of optical spectra recorded a few hours apart. No change of the optical spectrum is observed in the comb span that lies within a 20 dB power envelope. This remains the case until the fiber stretcher runs out of range. It is also observed that the comb profile is stable even when the reference laser suffers mode jumps.

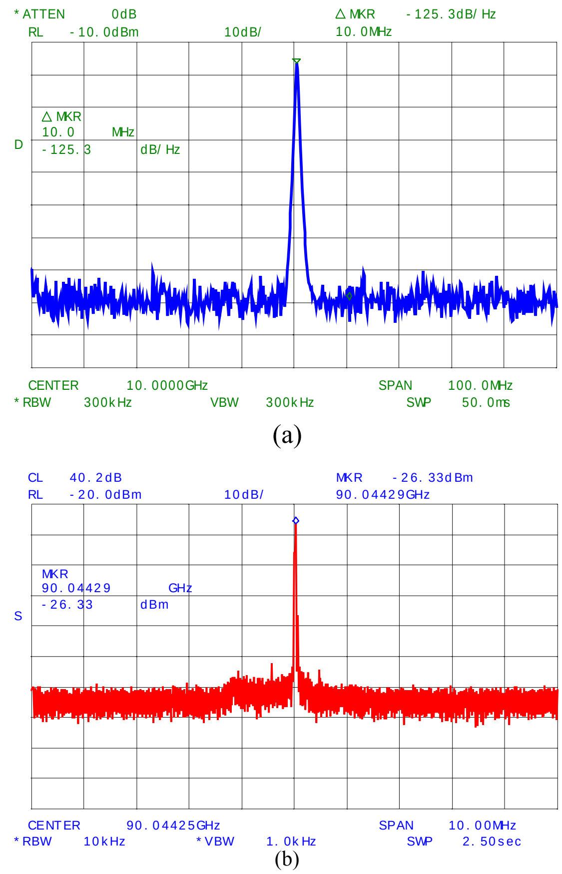


Fig. 8 The beat signal produced by the OFCG detected by a photodiode: (a) 10 GHz beatnote; (b) 90 GHz beatnote.

The comb span is linked to the modulation depth, the round-trip gain and the power level of the input optical reference. Fig. 7 demonstrates how the optical spectrum changes when the OFCG's RF drive power is increased from 0 dBm to 7 dBm (corresponding to phase modulation depth of 0.8 to 1.8). At lower RF power, the comb at shorter wavelengths suffers degradation. This degradation is due to the round-trip phase mismatching, to which the chromatic dispersion contributes, as discussed in Section III and shown in the theoretical results of Fig.3. With the increase in modulation power, and hence modulation depth, the degradation point is pushed away from the center of the comb.

The coherence between the comb lines is studied by using the comb to directly excite millimeter wave signals on a photodiode [14]. Fig. 8.a and Fig. 8.b shows the generated signals at 10 GHz and 90 GHz, respectively. These signals posses sub-Hz linewidth and have very low noise floor. Fig 9 shows the measured phase noises for 10 GHz, 20 GHz and 90 GHz signals, superimposed on the same graph. Where the noise is not limited by the measurement system noise floor, there is a clear relationship between the phase noise level and the multiplying order *N*. Apart from a slightly discrepancy in the offset range 300 kHz to 1 MHz, the noise follows a 1/f profile.

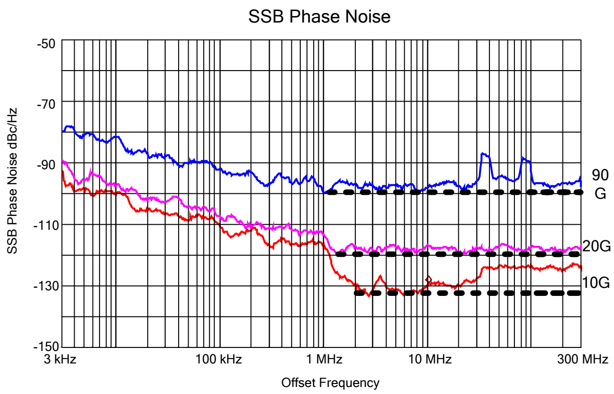


Fig. 9 The SSB phase noise performance for the OFCG directly beat on photodiodes. The traces are for 10 GHz , 20 GHz and 90 GHz. On the 90 GHz signal, the phase noise is limited by the measurement system from 1 MHz offset, and the peaks observed at 30 MHz and 90 MHz are spurs due to the harmonic mixer. Inserted dashed lines are the measurement system noise floor

Fast frequency switching of the OFCG is also demonstrated. It is found that the OFCG can work with any comb line spacing between 6 GHz and 12.5 GHz, limited by the bandwidth of the internal microwave circuit. No adjustment of the system is needed when the frequency switching is carried out. When switching back to the original frequency, the comb maintains its original profile. It is observed that after the adjustment of the RF frequency of the synthesizer, the optical comb is stabilized well within a second, limited by the updating speed of the optical spectrum analyzer. The switching speed, according to section III, should be no longer than a few milliseconds. This results in a very fast optical frequency switch, covering all possible frequencies within the OFCG comb width, with a resolution of 12.5 MHz and an accuracy of the stability of the reference light. This can be used to provide a stable and strong optical grid to many applications. It can also produce high stability millimeter and submillimeter wave signals at any desired frequency accurately, with the flexibility of fast frequency switching. Fig. 9 shows the optical spectra when the OFCG is adjusted from 6 GHz to 12.5 GHz at 500 MHz per step. The measurements were taken at 1 second intervals, limited by the scanning speed of the optical spectrum analyzer. Although a constant RF power of 6 dBm is maintained, the lower response of the microwave circuit and phase modulator at higher frequencies, results in lower modulation depth and therefore a similar comb slope is maintained across the tuned frequency range.

V. Conclusion

A frequency domain numerical model for the fiber ring based OFCG has been developed to allow the study of chromatic dispersion and other effects on the OFCG. It also allows the study of the spectral evolution in time. A very flat optical comb, with a 6dB power envelope over a terahertz span can be achieved using 10 GHz RF modulation. The OFCG operates with high power efficiency, requires only 0.5 mW of optical reference power and produces an optical comb containing hundreds of lines with a total power of 8 dBm. An improvement in the error correction circuit enables the OFCG to perform fast frequency switching in its comb line spacing. This switching can be done across an octave bandwidth between 6 GHz and 12.5 GHz with a resolution of 12.5 MHz.

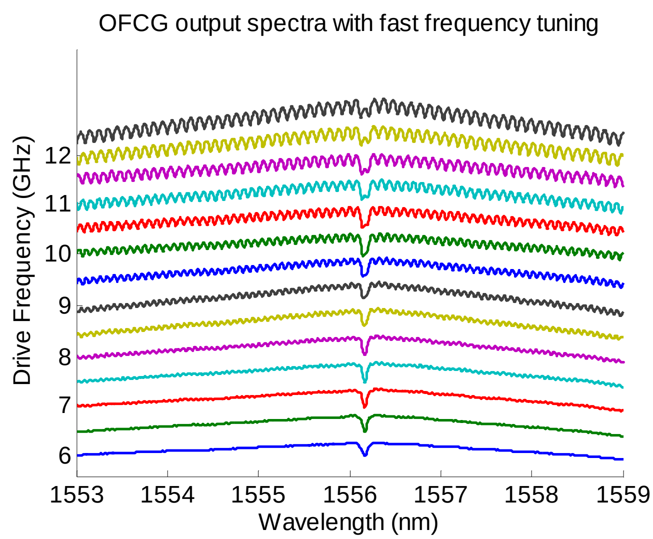


Fig. 10 The OFCG output optical spectra when the RF frequency is stepped from 6 GHz (lowest trace) to 12.5 GHz (top trace), at 0.5 GHz per step, at one second intervals. All comb spectra maintain a 6 dB power envelope of approximately 6 nm.

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