Fully Tunable LiNbO$_3$ Ring Resonator Cavity for Frequency Comb Generator (FCG)

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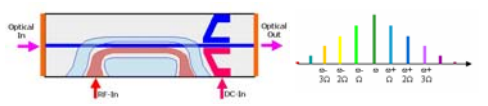
Introduction

Abstract:
A new type of tunable waveguide optical frequency comb generator (FCG) integrated in a LiNbO$_3$ (**LN**) ring resonator cavity is presented. The modeling of the integrated ring FCG, performance simulation and initial experimental results are described.

The most direct method of producing an FCG is to modulate a continuous wave optical signal using an electro-optical-modulator (EOM) crystal, which can be enhanced by placing it inside a resonant optical cavity, see Figure:



A waveguide type optical FCG based on a conventional Fabry-Perot electro-optic modulator (EOM) reportedly can produce a wide span of sidebands in the frequency domain or ultra short high repetition-rate optical pulses in the time domain [1-2]. So far, such devices were implemented mostly for precise optical frequency measurement or picosecond optical pulse generation that has been used, for example, in optical coherent sensing and tomography.
The optical cavity FSR (an integer number of fringe separations) should be adjusted to the modulation frequency, thus efficiently producing a comb by resonantly enhancing the modulation sidebands. The OFG modulation frequency sets the separation of the sidebands. By using traveling wave electrodes, in which the electrical signal propagates along the same direction as the optical wave, much higher bandwidths can be obtained and the resulting spectrum can be quite broad if the modulation frequency and modulation index are both high.

I. LN Fabri Perot FCG (conventional)

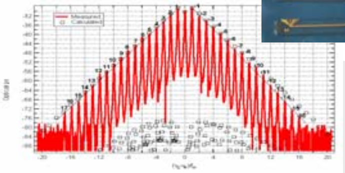
Concept: **LN EOM integrated into FP cavity**

$$f_m = N \times FSR = N\,\frac{c}{2L_c\,Ng}\,; \qquad \Phi = \frac{\pi(\nu_0 - \nu_{FP})}{FSR}$$

$$P_k = |Ei|^2 (1-r)^2 \left| f_m \int_{-1/2f_m}^{1/2f_m} dt\, exp\{-j2\pi f_m k t\}\, r^k\, exp\left\{-j\left(\frac{\pi\nu_0}{FSR}(2k+1) - m_k\right)\right\}\right|^2$$

$$m_k = m\,sin\left[2\pi f_m t - \pi\frac{f_m}{FSR}\right] \qquad for\ k = 0$$

$$m_k = m\,sin\left[2\pi f_m t - \pi\frac{f_m}{FSR}(k+1)\right]\left[\frac{sin\left[\pi\frac{f_m}{FSR}(k+1)\right]}{sin\left[\pi\frac{f_m}{FSR}\right]} - \frac{sin\left[\pi\frac{f_m}{FSR}k\right]}{\pi\frac{f_m}{FSR}}\right] \qquad for\ k \neq 0$$



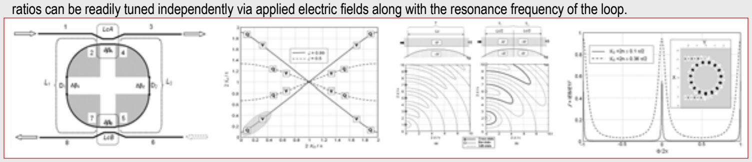
- **RF-travelling and biasing electrodes.**
- **Mirrors are coated directly onto the edges of EO LN crystal**
- **Parameters to control:**
- **The comb spacing & the frequency offset (translation)**

Motivation

Practically, however, optical sources with high stability, accuracy, well-controlled phase and cavity coupling are required in order to obtain a reliable wide spectral coverage or narrow pulse-train. There are some drawbacks limiting the performance of the conventional FCG. Thus, in order to transfer a large portion of the optical power to high-order sidebands, a high-finesse optical cavity and a highly efficient modulator are required. However, improving the cavity finesse only by increasing the mirror refractivity suppresses the total power of the generated sidebands, despite increasing the relative power transferred to the high order. In other words, the FCG output forms an optical pulse train whose peak power is limited by the total input laser power. By increasing the finesse (and/or modulating index) the pulse-width is narrowed while the peak power remains the same, decreasing the sidebands total power (average). Also, in order to provide a sufficient comb-span (number of teeth) the cavity size has to be relatively small even for the resonant order above 1. Such small dimensions (around 1-2 cm) require rather short RF traveling- and biasing electrodes. As a result, high Vpi, high modulating power, and difficult packaging become the factors that restrict the device applicability. In addition, the loss-dependent quality-factor of the resonator can be limited by the pre-fixed reflectivity of semitransparent mirrors that also make the cavity input coupling a difficult task.

II. Modelling of the ring resonator with tunable couplers: Optimized coupling

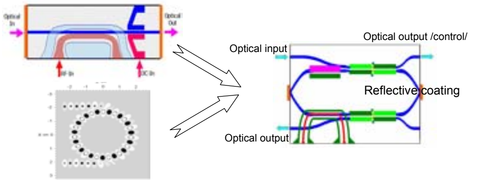
The optimization of the ring resonator cavity in a passive regime (no RF modulation) is described elsewhere [3] for different type of couplers. It was shown that for a lossy cavity the non-identical input/output coupling values are desirable for the optimal performance. Figures below show the quality/contrast optimization of such a passive ring resonator where the add/drop coupling ratios can be readily tuned independently via applied electric fields along with the resonance frequency of the loop.



- Optimal Ka-coupling values exist for each optimal passive coupling Kb.
- For the given losses, the resonant performance can be optimized either for max output contrast or better quality factor.

III. Integrated Ring FCG

In order to address all of the above-mentioned problems, a new type of FCG based on a ring-resonator with tunable add/drop coupling was developed. The main issue associated with the weakly-guiding LiNbO$_3$ (LN) ring cavity is the high radiative bend losses that restrict the minimal cavity circumference length needed for a reasonably large bandwidth. This issue was addressed by implementing a relatively low-loss compact “light-turning regions” developed by CeLight Inc. By this means the high bending losses can be substantially reduced. Single mode waveguides in LN were used to make an optical resonator by forming a certain waveguide configuration into a closed loop to constitute a low loss cavity.



Better design flexibility:

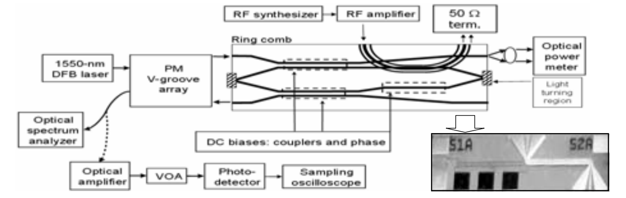
$$f_m = N \times FSR = N\,\frac{c}{\cancel{2}L_c\,Ng}$$

Add /drop couplings readily tuned

Fiber /cavity coupling is optimized

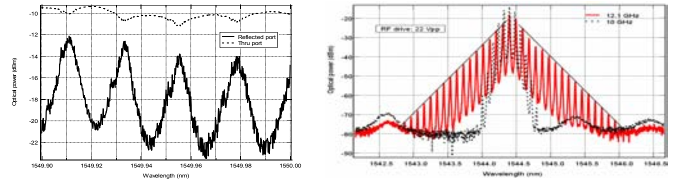
Ring Comb Device Characterization

A schematic view of the ring-cavity OFG and photograph of the device are shown in Figure:

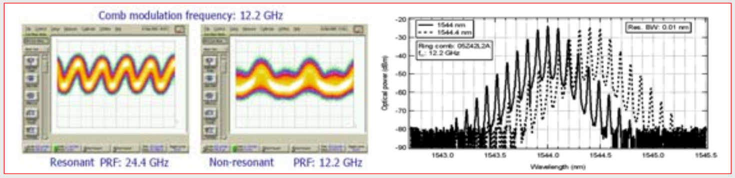


Ring FCG experiment

Two configurations of the ring FCG were realized with cavity lengths of ~2.25 and ~4.5 cm, both supporting ~6 and ~12 GHz modulating frequencies. An external 1550-nm DFB laser source was coupled into one of the bus waveguides of the ring resonator via a V-groove PM fiber array. The thru port of the comb output on the right side was directed to an optical power head using a focusing lens while the reflected port was fiber-coupled via the same V-groove array. RF and DC probes were applied to the traveling-wave, phase, and coupler electrodes of the device. Optical signal from the reflected port was monitored using an optical power meter, optical spectrum analyzer (OSA), and a 30-GHz sampling oscilloscope for monitoring of pulse train. RF signal was applied to the traveling-wave electrodes to produce phase-modulated output. Resonance of the comb was determined by an on-resonance (close to integer multiple of the FSR) and off-resonance RF drive frequency.
For high-resolution passive transmission spectrum extinction ratio, the DFB laser was replaced with a wavelength-tunable laser and an optical power meter was used to measure the optical power at the reflected output port of the ring FCG device. The ratio of the maximum to minimum optical power recorded in the spectral scan is the extinction ratio, which is related to the finesse of the resonator. Alternatively, a fixed wavelength laser can be used while the phase voltage of the comb device is swept to determine its spectral response. The left Figure below shows a typical spectral scan for particular ring FCG. Both reflected and transmitted optical powers versus wavelength are shown. The measured FSR was about 2.84 GHz and the extinction ratio for the reflected port output is about 8 dB.



The above Figure on the right shows OSA spectral output from the reflected port of FCG driven at 12.1 and 10GHz (on- and off-resonance, respectively). The resolution bandwidth of the OSA was 0.01nm. The RF drive voltage was about 22 V peak-to-peak. The slope of the comb envelope was estimated to be about -0.28 dB/GHz at resonance. With off-resonance drive at 10 GHz the number of wavelengths reduced drastically. The temporal output of the ring comb device was monitored using a sampling oscilloscope. The repetition rate of the pulse train varies between 12.1 and 24.2 GHz (on- and off-resonance, respectively). Several control loops for maintaining resonant FCG were suggested. One of the proposed control loops is based on a counter-propagating controlling laser, derived from the same external injected laser but launched counter-propagating to the RF traveling wave through the FCG. Thus, the clockwise-propagating control laser does not experience instantaneous phase modulation but only an average phase shift. By this means, the optical power of the control laser from the comb output can be used directly as a feedback signal to indicate whether or not the comb is in resonance.
Figure below shows pulse waveforms of the ring comb output displayed on the sampling oscilloscope with and without the resonant control loop running. The sampling oscilloscope was set to infinite persistent mode so that drift and fluctuations of the comb output can be accumulated and recorded. Note that the pulse waveforms shown in the figures are limited by the detection bandwidth (40 GHz) of the oscilloscope. With the control loop running, one can see from Fig. 14 that the ring comb device is maintained at resonance with a stable output pulse train at a repetition rate of about 24.4 GHz or 2*fm*. On the other hand, without the control loop the comb device seems to fluctuate randomly in and out of resonance causing the output pulse pattern to drift in time. As a result, no stable pulse train at 2*fm* was observed. The fluctuation can be attributed to variation of the injection laser optical frequency and environmental-induced perturbations on the refractive index of the LiNbO3 waveguide of the comb device.



The performance of the variable ring comb was verified by tuning the wavelength of the laser. The tunable laser was tuned from 1544 to 1544.4 nm with 0.1 nm steps. It was observed that with the control loop turned on resonance was maintained throughout the tuning range. Above Figure on the right shows typical optical spectra of the ring comb output at 1544 and 1544.4 nm as the tunable laser swept between these two wavelengths.

Summary

A new fully tunable integrated weak-guiding ring FCG device was presented for the first time, to our knowledge. Such a device potentially overcomes the limitations of existing integrated devices based on traditional Fabry-Perot cavities or ring cavities with limited tunability. Preliminary experimental results are encouraging and are consistent with simulation results. Future development will include the optimization of add/drop coupling tunability and cavity losses minimization through improving the light turning regions of the LN cavity. The resonant closed-loop control algorithm was also designed, developed, and tested for the first time. Future resonant control experiments of the ring comb will utilize both available optical and electrical outputs for a more robust performance. Presented ring structures with autonomous input/output coupling ratios and phase tuning are expected to have extensive and promising optical and high RF applications.

References

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[2] Fixed and Variable Optical Grid Comb Design Document, CeLight Inc., Technical Report Provided to Northrop Grumman for Secure Digital Coherent Optical Communications (SDCOC). Defense Microelectronics Activity (DMEA), 2005.
[3] A. Kaplan, “Modeling if Ring Resonator with Tunable Couplers”, *IEEE Selected Topics in Quantum Electronics*, Vol.12, pp. 86-95, 2006.

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