Tunable Frequency Comb Generator based on LiNbO$_3$ Ring Resonator

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

OCIS codes: (250.3140) Integrated optoelectronic circuits, (230.5750) Resonators

1. Introduction

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 Fig.1. 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.

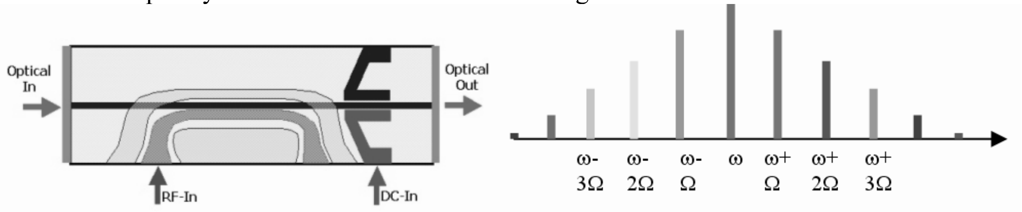


Fig. 1. Schematic illustration of LN integrated optical waveguide FCG.

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.

2. 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. A schematic view of the ring-cavity OFG and photograph of the device are shown in Fig. 2.

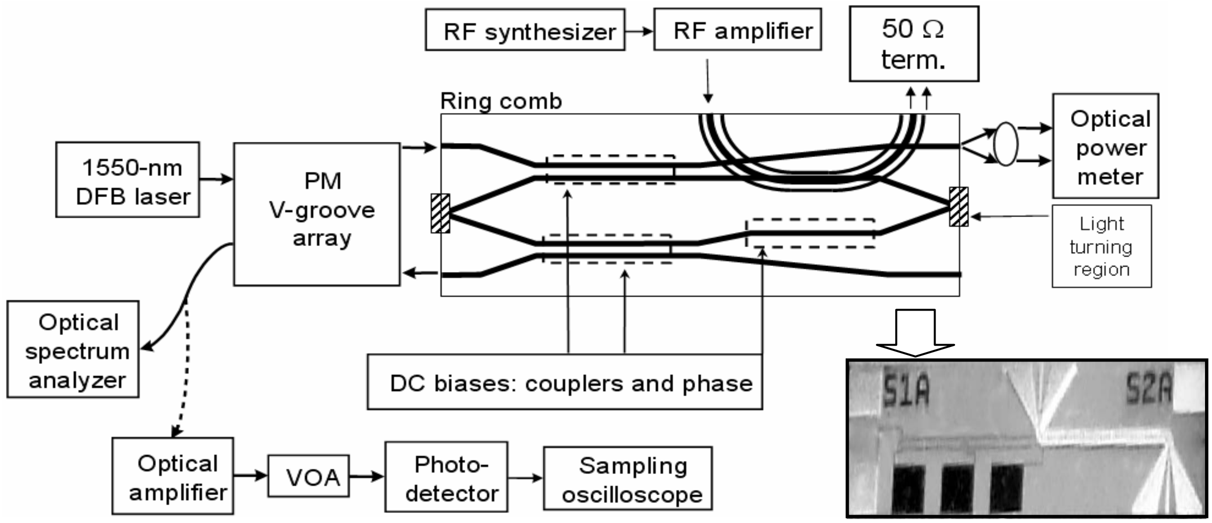


Fig. 2: Ring resonator optical comb schematic view and test setup. Inlay with actual device picture is shown.

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. Fig. 3 shows 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.

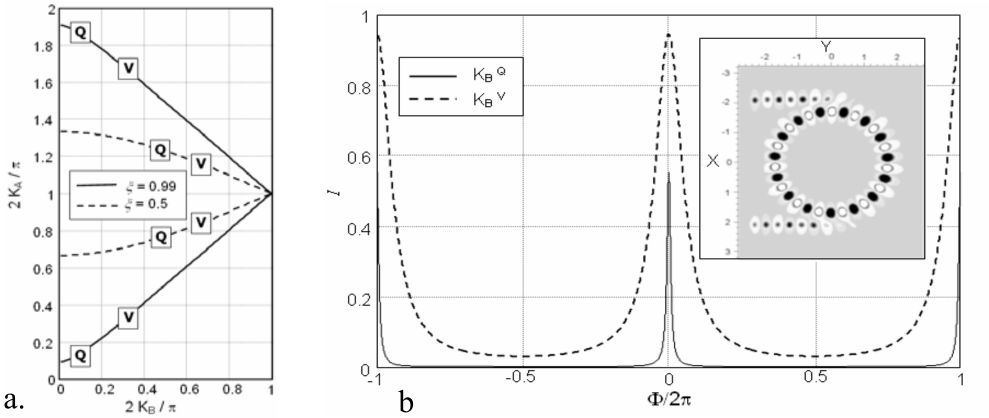


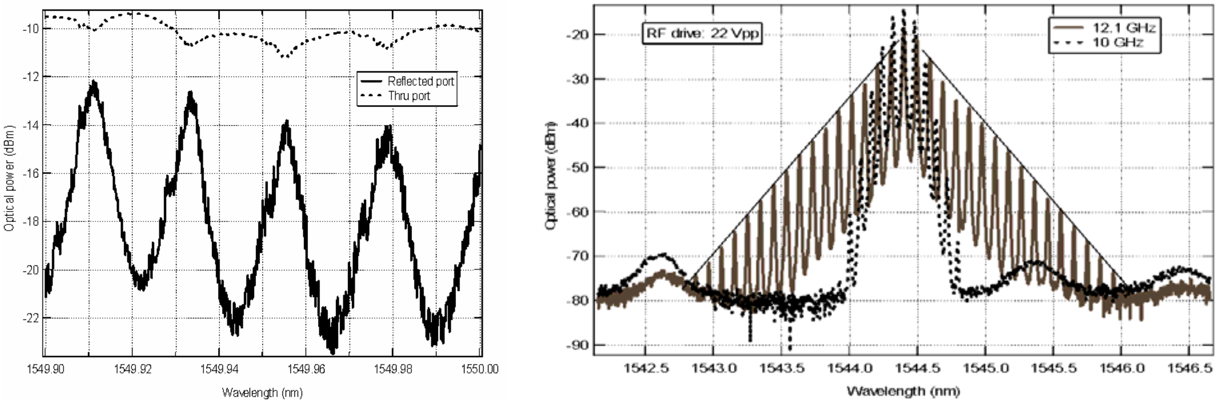
Fig. 3: a) Coupling dependence for the passive ring cavity at resonance. Marks indicate maximum resonator quality Q or contrast V given for two values of the cavity losses (1-ξ). b) Q- and V- resonator response optimization by passive design or by an external tuning; for ξ=0.99.

While having all the benefits of LN technology, such a ring FCG doesn't require semitransparent mirrors and add/drop coupling can be controlled via electro-optically adjustable couplers, resulting in improved applicability over ring structures with inseparable controls of cavity parameters, such as Whispering Gallery Mode cavities. In addition, the cavity circumference is matched to the doubled length of a conventional cavity under the same resonant regime, thus providing more space for electro-optical arrangements. Weakly guided technology also mitigates the fiber/waveguide alignment problem, providing an effective reciprocal coupling between fiber and the cavity.

3. 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. The test setup is shown in Fig. 2. 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. Fig. 4a 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.



a. b.

Fig. 4: a) Spectral scan of the reflected and thru ports of the ring OFG output. b) Optical spectrum of FCG reflected port output with drive frequency of 12.1 GHz (near resonance) and 10 GHz (off-resonance). Resolution bandwidth: 0.01 nm.

Fig. 4b 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 as shown in Fig. 2. The repetition rate of the pulse train varies between 12.1 and 24.2 GHz (on- and off-resonance, respectively). An estimated finesse and modulation index was about 3.62 and 2.2, 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.

In 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.

4. References

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