Electro-Optical Frequency Comb Generator Based on Electrical and Optical Dual Resonance Enhanced Structure

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Abstract : *An electro-optic frequency comb generator based on electrical and optical dual resonance enhanced structure is proposed. The theoretical analysis and experimental measurements demonstrate that the modulation depth of the standing-wave electrode is increased by 2.3 times, and the spectral bandwidth is extended to 1.7 times.*

Introduction

Optical frequency combs (OFC) are used in a wide range of applications, from precision metrology and timing to spectroscopy and optical communications [1-3]. In optical communications, it is ideal that the frequency comb feature an adjustable free spectral range (FSR) [4], as well as a flat spectrum and strong coherence. Therefore, the EO frequency comb is a suitable candidate.

Due to the strong electro-optical effect and the development of thin-film lithium niobate (TFLN) integration platform, EO frequency combs based on TFLN have received considerable attention. Although extensive studies and remarkable progress have been made towards the high-performance EO frequency combs based on microresonator [5-8], the transmission loss of RF signals still hinders the further improvement of the modulation depth. The power of the comb line, $q \times FSR$ far from the pump, is as follows:

$$P_q \propto e^{-\frac{2\pi\omega_0|q|}{FSR(\omega)\beta Q_{load}}} \tag{1}$$

where ω_0 is the angular frequency of the pump light, β is the modulation depth, and Q_{load} is the loaded quality factor of the optical microresonator. As shown in the formula, the increase in modulation depth β has a similar function as increasing in the Q factor. However, the latter relies heavily on the fabrication process, which is quite challenging for the micro/nano fabrication.

In this paper, we proposes an electrical and optical dual resonance enhancement structure for the electric-optic comb generation. Compared with the common EO comb generator based on microresonator, the ordinary traveling wave electrode (TWE) is replaced by the standing wave electrode (SWE) of the Fabry-Pérot cavity (FP) to strengthen the microwave electric field and hence to improve the modulation depth.

Design and fabrication

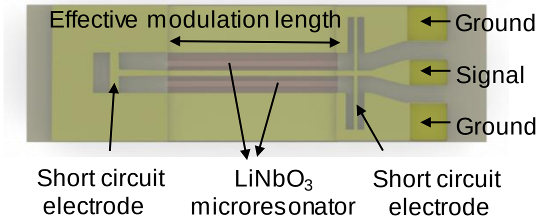


Fig. 1: Schematic diagram of the proposed SWE

The electrode structure affects the modulation electric field on the optical waveguide, which is an important factor in determining the modulation depth β. In order to realize the integration of the modulation structure and the waveguide microresonator, the electrode structure of the coplanar waveguide (CPW) type is preferred. Figure 1(a) shows a schematic structure of the device that uses a CPW GSG electrode structure to modulate the optical field in the microresonator, where the signal electrode and ground electrodes are on the same plane for easy integration. When the impedances of the input and output ports match the 50 ohm characteristic impedance, it is the classical CPW TWE structure. When they mismatch, the electrodes will provide a certain microwave reflection, thereby constituting an FP resonant cavity for the microwave signal. When the microwave frequency is at resonance of the FP cavity, the electric field of the modulation signal will be effectively enhanced.

In a TWE, modulation phase shift $\Delta\varphi$ can be approximated as formula (2)

$$\Delta\varphi = \beta e^{-i\omega_m t} \tag{2}$$

While in a SWE, the modulated phase shift $\Delta\varphi^{FP}$ can be approximated as:

$$\Delta\varphi^{FP} = \frac{t_1 + t_1 r_2 \alpha^2}{1 - r_2 r_1 \alpha^2}\beta e^{-i\omega_m t} = (B \cdot \beta) e^{-i\omega_m t} \tag{3}$$

where the self-coupling coefficient and cross-coupling coefficient of the direct waveguide are r_1

and t_1, respectively, and the self-coupling coefficient and cross-coupling coefficient of the microresonator are r_2 and t_2, respectively, α is the transmission loss, and B is the modulation enhancement factor of the SWE relative to the TWE, which is the ratio of the modulation depth of the SWE to the TWE.

In order to achieve the FP cavity structure of the SWE, a short-circuit electrode structure based on a coplanar waveguide is used to form a reflective interface of the microwave FP cavity, which can introduce discontinuities of the coplanar waveguide [9]. This structure which is easy to integrate into the electrode, can control the reflection and transmission rather freely. Schematic diagram of the proposed SWE is shown in Figure 1.

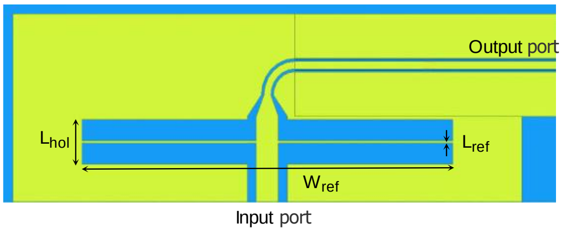
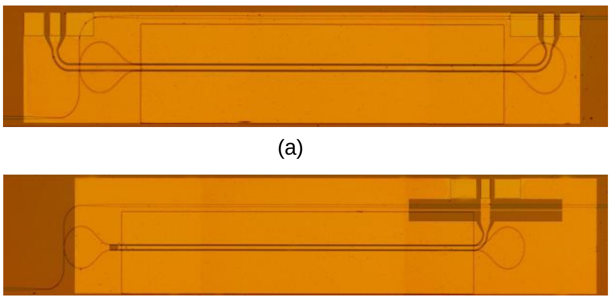


Fig. 2: Schematic diagram of the input port of the SWE

As shown in Fig. 2, the parameters of the short-circuited electrode at the input port are as follows: short-circuit electrode length W_{ref} =900 μm, metal electrode hollow length L_{hol} =105 μm, Considering the fabrication tolerance, short-circuit electrode width L_{ref} is designed to be 1.5, 2.5 and 5 μm. The EO frequency comb generators based on TWE and SWE modulation structures has been fabricated, and the microscope images of the fabricated devices are shown in Fig. 3(a) and Fig. 3(b), respectively.

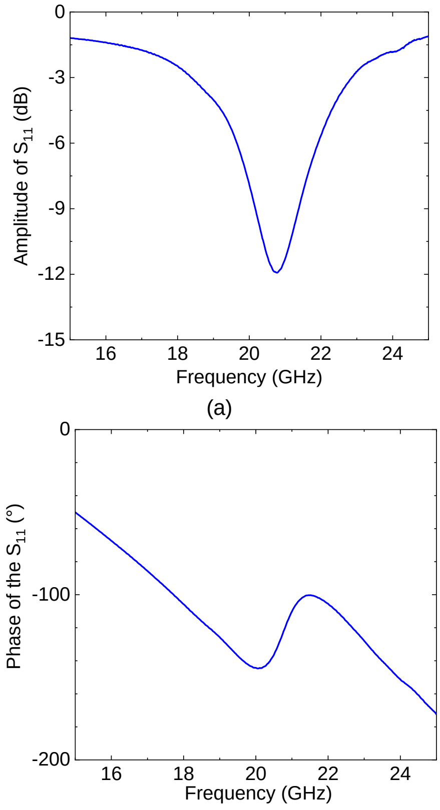


(a)

(b)

Fig. 3: (a) Microscope image of the TWE, (b) microscope image of the SWE.

Experimental results



(b)

Fig. 4: (a) Amplitude of the S_{11}, (b) phase of the S_{11}.

The S parameter of the SWE is measured when L_{lef} is 5 μm, and S_{11} is the scattering coefficient of interface of input port. Due to the resonance of the FP cavity, the amplitude of S_{11} is measured to be the Lorentz curve, as shown in Figure 4(a), the phase of the S_{11} is shown in Figure 4(b), which will abruptly change near the resonant frequency, and the resonance frequency of the SWE is 20.76 GHz.

The optical parameters of the EO frequency comb are measured as follows: FSR = 20.42 GHz, t_2 = 0.4184, α = 0.5822, the pump power is 0.16 mW, the peak voltage of the modulation signal is 2 V. The β calculated by simulation is 0.11×π, and the simulated TWE-EO comb is shown in Fig. 5(a), which has 6 pairs of sidebands with an attenuation slope of the modulation comb line can be calculated to be 54 dB/nm.

The measurement results of the TWE-EO frequency comb are shown in Fig. 5(b) with f_m is 20.3~20.5 GHz. The average attenuation slope of the comb lines is estimated as 55 dB/nm, which is consistent with the simulation results. The maximum bandwidth of the TWE-EO frequency comb of this structure is 1.64 nm.

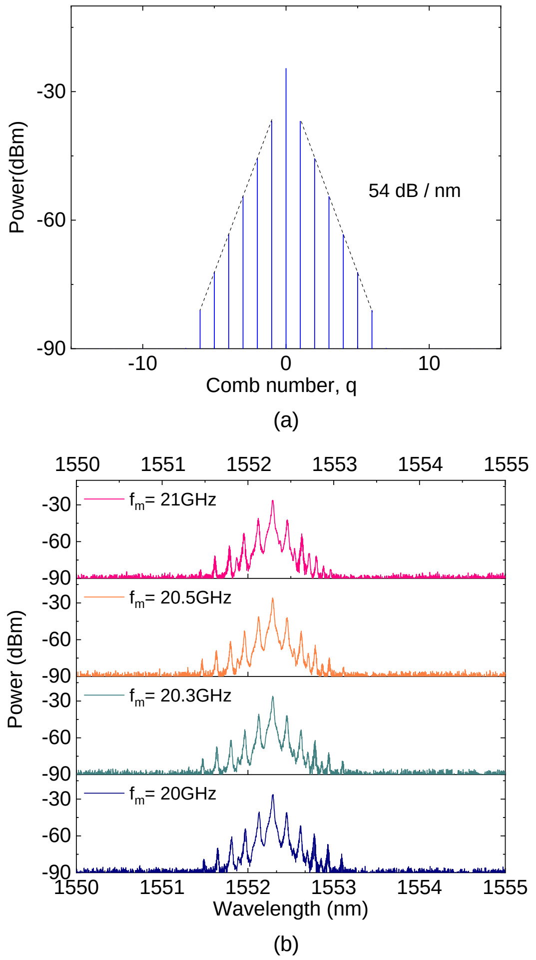


Fig. 5: (a) Simulation results of TWE-EO comb. (b) the measurement results of the TWE-EO comb with different f_m.

the B of the SWE can be calculated to 2.34 according to the S, which illustrates that the β of SWE is increased by 2.3 times compared with that of the TWE. Considering the B of the SWE, the simulated results of the SWE-EO frequency comb is plotted as Fig. 6(a). It is seen that there are 14 pairs of sidebands with an attenuation slope of the modulation comb line is about 24.1 dB/nm.

The measurement results of the SWE-EO frequency comb is shown in Fig. 6(b). The attenuation slope of the sideband comb teeth is significantly reduced to 35.7 dB/nm, which is similar to the simulation results. The widest comb is 2.79 nm, which is extended to 1.7 times compared with the TWE-EO comb.

These results demonstrate the improvement of the SWE structure on the modulation depth, and the microwave resonance enhancement structure is benefical for expanding the spectral bandwidth of the EO comb. The spectral bandwidth of the EO comb is narrower than expected due to the electrical and optical loss is relatively high from this fabrication run which will be improved in the near future.

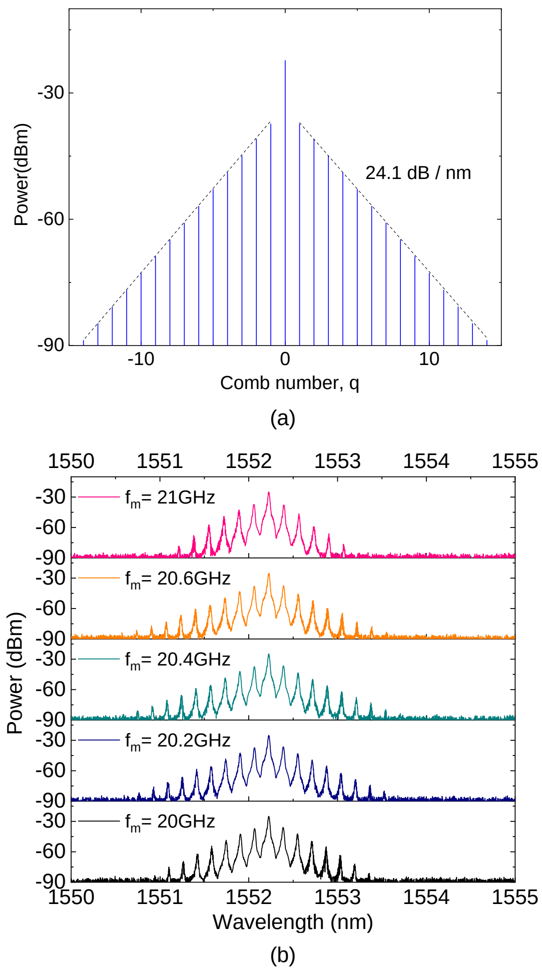


Fig. 6: (a) Simulation results of the SWE-EO comb when the f_m matches characteristic frequency of the FP cavity and FSR of microresonator with $L_{ref} = 5$ μm, (b) measurement results of SWE-EO comb with different f_m.

Conclusion

We have proposed an EO comb generator based on electrical and optical dual resonance enhancement structure which adopts the SWE to achieve the resonance enhancement of the electric field, and realizes the resonance enhancement of the light field through the microresonator. It is proved by simulation and experiments that the β of SWE-EO comb generator is increased by 2.3 times, and the spectral bandwidth is extended to 1.7 times compared with that of the TWE-EO comb. Therefore, the SWE structure is more promising for better performance of the EO comb.

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