The Optical to Electrical Conversion of a Frequency Comb and Related Applications

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***Abstract*—Based on the technique of TL's optical frequency comb (OFC), an alternative and feasible way for measuring microwave frequency up to 80 GHz has been implemented in our recent experiments. Conventionally, an OFC serves as a very accurate optical frequency measuring tool when frequency-stabilized to an external reference. Beat frequency (δf) between an unknown optical frequency source and an OFC could be obtained by using a photodiode carrying out the O/E conversion and the measurement result be determined. In our lab, when utilizing the one with bandwidth hundred times larger than the OFC's repetition frequency (fr), we obtained an additional microwave frequency comb, which was derived from the original OFC only with the same O/E effect. In order to figure out capability of the counterpart, we used the simulating DUT (device under test) composed of frequency synthesizers, frequency multipliers, power amplifiers, mixers, etc., for its performance evaluation. The experimental results showed that operating range of the derived comb was somewhat wider than the photodiode's bandwidth claimed, so this proposed method seemed promising in providing another way for characterizing signals in microwave frequency domain, which was practiced by using common microwave frequency instruments before.**

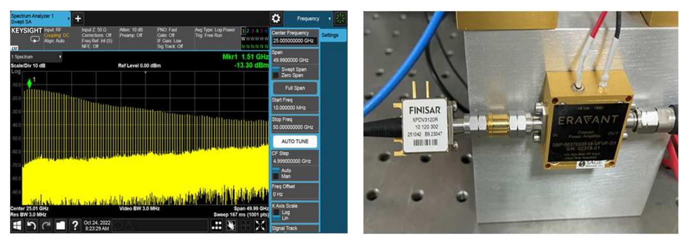
Keywords—optical frequency comb; photodiode; conversion; bandwidth; repetition frequency

I. INTRODUCTION

Our OFC (ITRI ER500) is a compact one based on an ultrafast mode-locked (ML) erbium-doped fiber laser with a 500 MHz repetition frequency and provides octave-spanning spectrum covering 1100-2200 nm (or 136-272 THz). In addition to the supercontinuum (SC), a 1550 nm output and a 760-900 nm second harmonic generation (SHG) are also available [1]. Comb line of the OFC has a frequency that is an integer multiple of the repetition frequency (fr) plus a carrier-envelope offset (CEO) frequency (fo), i.e. fn=n*fr+fo, where n is the ordinal comb number. When the laser light is transmitted to a photodiode, signals with microwave frequency, fn= n*fr, could be generated and a microwave frequency counterpart obtained due to the O/E conversion.

In 2020, we set up a conversion prototype using an external Finisar XPDV3120R photodiode (~70 GHz) connected to the 1550 nm output of our OFC. Although signals of the derived microwave frequency comb could be observed on a spectrum analyzer (SA) obviously, performance of the individual comb lines was further evaluated by precisely frequency beating with the simulating DUT, which was made with combinations of microwave frequency synthesizers and related devices. Comb lines up to 60 GHz were measured reasonably from beat frequencies with signal-to-noise ratio (SNR) not less than 40 dB at that time [2].

However, the experimental results seemed not to fully reach the claimed limit of the used photodiode. From the above SA, we observed that the comb lines with higher frequencies approximately had lower peak powers and signal-to-noise ratio (SNR) as shown in Fig.1 (a), which might explain the poorer results near the limit. In 2022, we made some improvements in combinations of the simulating DUT and the related to have better beat frequencies with the derived comb near the limit, particularly by using appropriate power amplifiers in the experimental processes as shown in Fig.1 (b), and the feasible comb lines was promoted to 70 GHz [3]. In this year, the result was pushed to a higher 80 GHz level with great frequency stability, which exceeded our previous expectations.



(a) **(b)**

Fig.1. (a) The derived comb observed on a spectrum analyzer (DC~50 GHz) (b) A microwave frequency power amplifier (50~70 GHz, 30 dB gain) connected to the Finisar XPDV3120R photodiode

II. METHODS/RESULTS

In the experiments, the 1550 nm output of our OFC with optical power≈ 10 mw was fed into the same photodiode and the derived comb power amplified (50-70 GHz) with 30 dB gain for subsequent frequency beating with the simulating DUT. Two frequency synthesizers (40 & 26.5 GHz) playing as the major roles for the simulating DUT were set purposely to obtain a presumed 10 MHz beating signal with the specified comb lines, as shown in Fig.2. In fact, frequency beating were carried out twice inside the simulating DUT of our design. The final 10

MHz output could be measured by a SR620 time interval counter and characteristic of the specified comb line evaluated. Five comb lines with frequencies of 72, 74, 76, 78 and 80 GHz were inspected and measured by this method. When the OFC and frequency synthesizers inside the simulating DUT were all referenced to the same hydrogen maser (common clock test), the Allan Deviation (ADEV) at τ=1 s for the five comb lines were all about 1.0E-12 and better than 1.0E-13 at τ=100 s as shown in Fig.3.

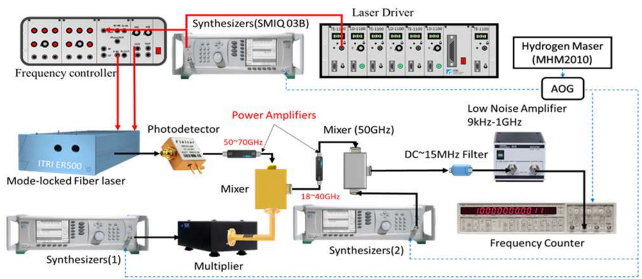


Fig.2. Block diagram of performance evaluation of the derived comb

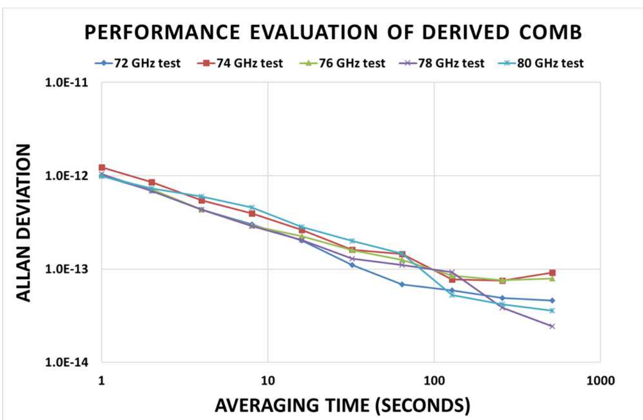


Fig.3. ADEV results of testing five frequencies of the derived comb

III. DISCUSSION/INTERPRETATION

When comparing the ADEV result of the present 80 GHz test with those ones related to 40, 50, 60 GHz tests in our former works, we found the comb line with frequency of 80 GHz was a little noisier than the others. The claimed limit of the used Finisar XPDV3120R photodiode might be the reason. Moreover, when comparing the same 80 GHz result with the one related to 26.5 GHz test using traditional microwave instruments without the OFC [4], we found the frequency stability degraded from 3.5E-13 to 1.0E-12 at τ=1 s. It seems very reasonable that we attribute these extra noises to the O/E conversion of our OFC and to the frequency beating processes for performance evaluation of the derived comb lines. Fig.4 shows the ADEV comparison results with 4 solid lines (with the O/E conversion) and one dashed line (without the O/E conversion).

Meanwhile, in order to further expand operating range of the derived comb, there are two approaches on going these days. First, use a photodiode with wider bandwidth instead of the present one for the O/E conversion. For example, the bandwidth of a Finisar XPDV 4121R photodiode can reach to 100 GHz. Second, adopt microwave frequency devices with waveguide adaptors inside the simulating DUT for reducing transmission loss more effectively in signal processing.

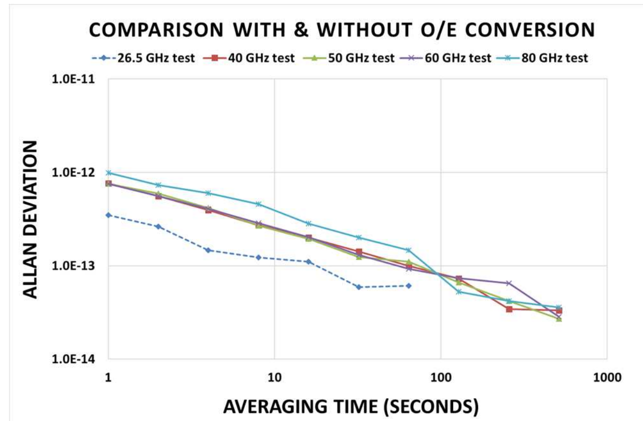


Fig.4. ADEV comparison results with (solid lines) and without (dashed line) the O/E conversion

IV. CONCLUSIONS

In our recent woks, the derived microwave frequency comb was verified to measure up to 80 GHz with great frequency stability. Although the O/E conversion of our OFC and performance evaluation of the comb lines may increase some noises in the measurement results, it is still optimistic that the derived comb would be an alternative and a useful tool in the microwave frequency measurement. We will continue to push its measurement limit and reduce unnecessary noises discussed above in the future works.

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