A Frequency Shifting Scheme for On-chip Optical Frequency Transfer

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***Summary*—We report a frequency shifting scheme for on-chip optical frequency transfer with low external circuit requirements. Serrodyne modulation method is used to achieve frequency shifting with high carrier and sideband suppression ratios for optical carriers, and the method is also suitable for a wide range of integrated platforms. We first demonstrate the feasibility of the scheme using a commercial phase modulator, which is able to produce a frequency shift of over 1 MHz, a carrier suppression ratio of over 50 dB, a sideband suppression ratio of over 37 dB and a conversion loss of about 0.08 dB. We also design a phase modulator on thin film lithium niobate platform with a low half wave voltage about 2.18 V, which greatly reduces the requirements of the external circuit voltage for frequency shifting, and can achieve a frequency shift above 1 GHz. Our proposed scheme verifies the feasibility of on-chip frequency shifting with low loss and high suppression ratio, and paves the way for the integration of optical frequency transfer systems.**

Keywords—optical frequency transfer, frequency shifting, serrodyne modulatio， phase modulator, thin film lithium niobate

I. INTRODUCTION

With the rapid development of optical frequency standard technology, more and more optical frequency transmission systems and networks have been reported [1][2]. However, most reported optical frequency transfer systems are based on discrete devices, and their large size is not conducive to large-scale production. If the optical frequency transfer system is integrated on a single chip, not only the size of the system can be reduced, but also the uncommon path can be shortened, thus improving the stability of the optical frequency transfer system. In optical frequency transmission systems implemented by discrete devices, acousto-optic modulators (AOMs) are used to provide frequency shifting for optical frequency signals to distinguish forward and backward signals and compensate the phase noise introduced in the optical fiber links or free space links as well. However, it is very difficult to realize frequency shift on chip by using acousto-optic effect no matter it is silicon platform or lithium niobate platform [3], and it is necessary to explore a new path to implement the on-chip frequency shifting scheme.

On-chip frequency shifting schemes based on carrier suppression single sideband modulation have been reported in recent years. However, since most of these schemes use IQ modulators [4][5] to realize the modulation, it will bring a insertion loss of at least 4.7 dB and cannot achieve bidirectional frequency shifting. Thus, such schemes are not suitable for the application of optical frequency transmission. The frequency shifter [6] on lithium niobate platform based on double-microring electro-optic modulation seems to have the advantages of large bandwidth and capable of bidirectional frequency shifting, but it has higher requirements on manufacturing process and is sensitive to fabrication tolerances.

Based on the serrodyne method [7], we propose a frequency shifting scheme suitable for on-chip optical frequency transfer systems. Such scheme does not need complex external control, and the only needs for the on-chip design is to realize the low half-wave voltage phase modulator, and such structure is simple and easy to be integrated on a large scale.

II. METHODS

The principle of serrodyne modulation is shown in Fig. 1(a). Where, $s(t)$is the sawtooth signal with a frequency of f_0 as Fig. 1(b) shows, Vpp is the peak-to-peak value of $s(t)$, T_0 is the period of $s(t)$and r is the ratio of the falling time of the sawtooth signal to the period. Supposing that the optical carrier signal can be represented as: $E_0 exp(2\pi v t)$, where v is the frequency of the optical signal. If we use a sawtooth signal with a falling time can be negligible to modulate the optical carrier by a phase modulator with a half wave voltage of V_π, the output signal will have a form of: $E_0 exp\left(2\pi\left(v+\frac{Vpp}{2V_\pi}f_0\right)t\right)$. Thus, when $Vpp=2V_\pi$, the optical frequency can have a frequency shift of f_0.

We first verify the principle with a commercial phase modulator with a half wave voltage of about 3.7 V and set up a heterodyne detection experiment structure for frequency shift test as Fig. 1(c) shows. To facilitate the testing of frequency shift effect, we use an acousto-optic modulator (AOM) to provide a 38 MHz frequency shift as the carrier signal, and an arbitrary waveform generator (AWG) to generate a sawtooth signal with a frequency of 1 MHz to modulate the phase modulator.

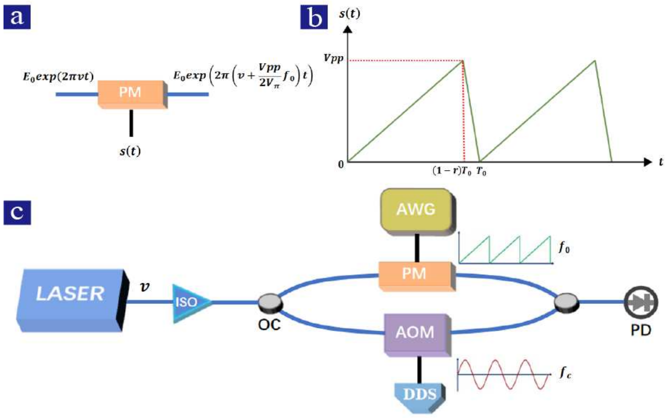

Fig. 1. (a) Principle of the serrodyne modulation. (b) The sawtooth signal. (c) The block diagram of the experimental test of the frequency shifting scheme. ISO: Isolator, OC: Optical Coupler, PM: Phase Modulator, AWG: Arbitrary Waveform Generator, AOM: Acousto-optic Modulator, DDS: Direct Digital Synthesizer, PD: Photodetector.

The test results is shown in Fig. 2(a) indicating that the optical carrier signal does produce a frequency shift of 1 MHz. When the peak-to-peak value of the modulated signal is about 7.4V, the carrier suppression ratio is about 50.75 dB, and all the sideband suppression ratio exceeds 37 dB. In addition, we also test the conversion loss, which is as low as 0.08 dB. On the basis of the experimental test, we carry out a theoretical modeling of the frequency shifting scheme, and the results obtained by simulation and experimental test show a good agreement. In addition, we also study the influence of the falling time ratio of the sawtooth signal on the carrier suppression ratio and sideband suppression ratio as Fig. 2(b) shows. The results demonstrate that when the falling time takes up less than 1 % of the whole cycle, the carrier suppression ratio of each sideband can always exceed 35 dB and keep the carrier suppression ratio over 50 dB.

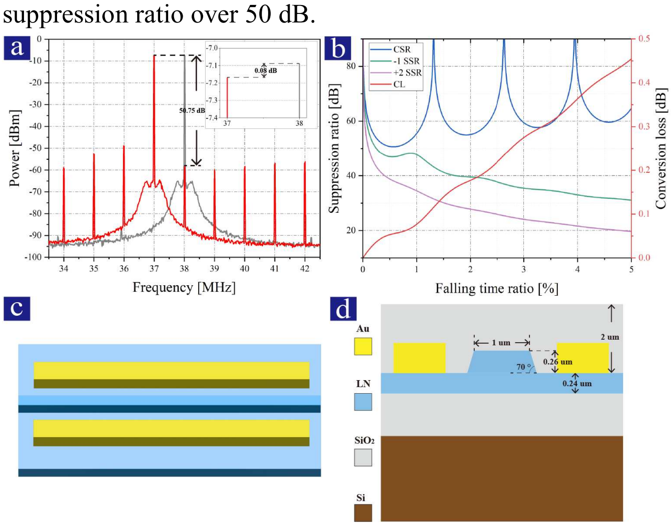

Fig. 2. (a) The test result of the frequency shifting scheme, the gray line is the carrier signal and the red line is the signal after serrodyne modulation. (b) The results of the suppression ratio and conversion loss at different falling time ratio. (c) The structure of the phase modulator on thin film lithium niobate. (d) The cross-section of the lithium niobate waveguide.

In addition, due to the excellent electro-optical effect, we have also designed a phase modulator with a half wave voltage of 2.18 V on the thin film lithium niobate as Fig. 2(c) and Fig.2(d) shows. The phase modulator is fabricated on an X-cut lithium niobate film with a thickness of 500 nm, an etched depth of 260 nm and the waveguide width is 1 um. The bandwidth of such phase modulator is over 1 GHz. Thus, the required frequency offset for optical frequency transfer system can be generated when the phase modulator is modulated by the sawtooth signal with a frequency less than 1 GHz.

III. DISCUSSION

The results show that the commercial phase modulator can realize the frequency shift with high suppression ratio and low requirement on the modulated signal. When the falling time ratio is less than 1 %, both carrier and sideband suppression ratio can exceed 35 dB, which can meet the requirements of optical frequency transmission system. For integrated system, low half-wave voltage phase modulators are needed. Thus, experimental verification tests should be conducted on the frequency shifting scheme carried out by the integrated phase modulator to prove the feasibility of the frequency shift scheme of the on-chip optical frequency transfer system.

IV. CONCLUSIONS

In summary, we proposed a frequency shifting scheme suitable for on-chip optical frequency transfer, which greatly reduces the need for external circuits. The tested results showed that the carrier suppression ratio can exceed 50 dB and the all the sideband suppression ratio is greater than 37 dB by using the commercial phase modulator with a half wave voltage of 3.7 V. We have also completed the design of an on-chip phase modulator with a half wave voltage of 2.18 V, which further reduces the circuit requirements for an integrated optical frequency transfer system. The proposed frequency shifting scheme is conducive to the large-scale integration and application of optical frequency transmission systems.

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