

Technique for translating light-wave frequency by using an optical ring circuit containing a frequency shifter

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A new technique for the external frequency translation of light waves is proposed. The technique enables the stepwise sweeping of an optical frequency in time over a wide range. The frequency translator is composed of an optical pulse modulator and an optical ring circuit that contains an acousto-optic frequency shifter and an optical amplifier. The pulse launched into the ring circuit undergoes a frequency shift for each complete trip around the ring circuit, and the frequency is translated considerably from the original input pulse. We confirm a frequency translation of as much as 8 GHz for a 1.5- μm light wave, in which the sweeping is strictly linear with respect to time.

Frequency translation or sweeping is an important technique in many areas such as light-wave communication,¹ optical measurements,^{2,3} and laser spectroscopy.⁴ In particular, highly accurate and controllable frequency translation are required. For example, a tunable frequency standard is required for coherent frequency-division-multiplexing transmission systems in order to stabilize multiple optical carrier frequencies arranged with a frequency interval of more than 5 GHz.¹ If stepwise frequency translation in time is possible with a constant frequency step width, it can be combined with the conventional frequency-fixed standard to realize a highly accurate tunable frequency standard. Areas of optical measurement such as coherent optical frequency-domain reflectometry² (C-OFDR) demand highly linear frequency sweeping. C-OFDR is based on the interference between a reflected and a reference light wave, in which their frequencies are swept as a sawtooth function against time and the optical path difference between the two waves is translated to the corresponding frequency difference. Therefore high linearity is essential in order to maintain a constant frequency difference for any optical path difference. It should be mentioned that C-OFDR does not necessarily require continuous frequency sweeping. Stepwise frequency sweeping with a constant frequency step width can also be employed with the condition that the time width of one step is adjusted so that it is shorter than the trip time for a distance corresponding to the spatial resolution.

External frequency modulators such as LiNbO₃ modulators and acousto-optic (AO) frequency shifters have been used to shift the light-wave frequency. However, the application areas of these external modulation methods are limited for the following reasons: (i) for an AO frequency shifter, the absolute frequency translation value is ~ 100 MHz, and frequency sweeping over a wide range is difficult in principle, and (ii) for a LiNbO₃ modulator, the frequency conversion efficiency is not high, and it is difficult to remove high-order components.

Another method for frequency translation is direct modulation,⁵ in which laser light-wave sources are directly controlled thermally or electrically and frequency translation of the order of 10 GHz is easily achieved. However, the accuracy and controllability are insufficient for the above applications. In this Letter we propose a new technique for the external frequency translation of light waves. This technique enables strict stepwise optical frequency sweeping with respect to time.

The external frequency translator is composed of an optical pulse modulator and an optical ring circuit containing an AO frequency shifter, an optical amplifier, and a bandpass filter as shown in Fig. 1(a). A continuous light wave is modulated into a pulse sequence by the optical pulse modulator and directed into a 50/50 fiber coupler. Half the pulse power is extracted as output, which we call the original pulse. The other half is launched into the optical ring circuit, amplified, and frequency shifted by an amount f by the AO frequency shifter. Then the pulse returns to the coupler and is divided again into an output and a recirculating pulse. Here the output pulse can be regarded as the first frequency-shifted pulse.

If the amplification gain of the optical amplifier is sufficient to circumvent optical loss in the circuit, pulse recirculation can be continued, and the light-wave frequency is easily translated from that of the original pulse with a constant frequency step in constant time at every circulation. In addition, if the circulation trip time around the ring circuit is adjusted so that it has the same value as the optical pulse width, the output pulse sequence from the ring circuit can be regarded as a continuous light wave. Although this is not essential to the technique, we assume this situation for simplicity in the following.

To realize the periodic repetition of the stepwise frequency sweep, the AO frequency shifter is synchronously controlled with the pulse modulator. As shown in Fig. 1(b), the AO frequency shifter is switched to the on state when the front of the input pulse reaches it. Pulse reproduction and frequency translation continue as long as the on state is main-

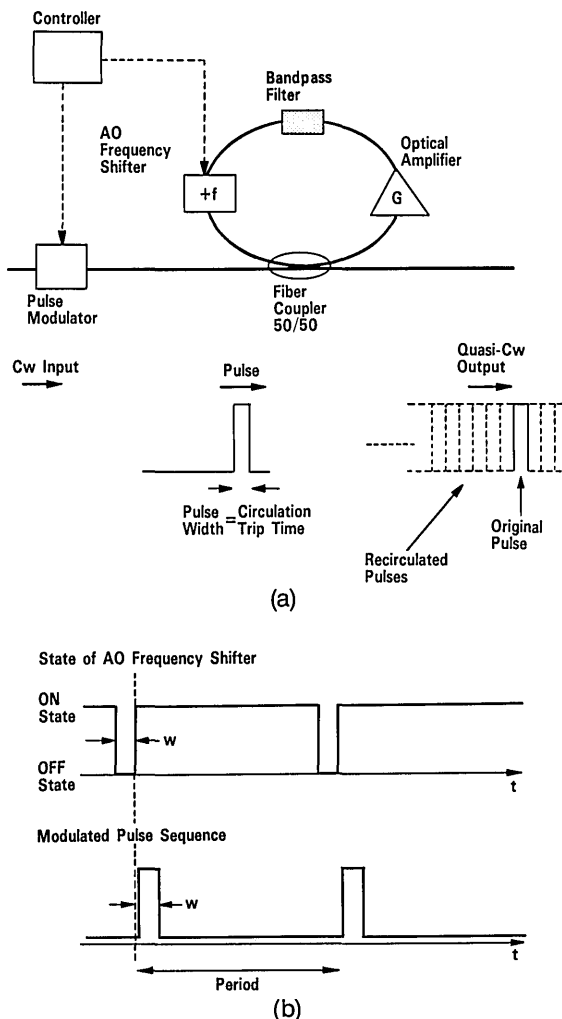


Fig. 1. Arrangement and operation of the frequency translator: (a) basic configuration of the proposed frequency translator, (b) synchronous control of the AO frequency shifter and the pulse modulator.

tained. Just after the passage of the last recirculated pulse, the AO shifter is switched to the off state as shown in Fig. 1(b), where the AO frequency shifter is also used as an optical switch. To prevent overlapping between the last recirculated pulse and the next externally input pulse, the off-state time is adjusted so that it is the same as the optical pulse width w , as shown in Fig. 1(b). Therefore the front of the next input pulse connects with the back of the last recirculated pulse, and we obtain a quasi-continuous light wave whose frequency is swept stepwise; the frequency sweep is repeated periodically. The maximum circulation number is determined by the ratio of the repetition period of the modulated pulse to the pulse width of the input pulse sequence.

The experimental setup is shown in Fig. 2. The continuous light wave of a single-frequency erbium laser with a wavelength of 1530 nm is divided into signal and reference light waves with a 90/10 fiber coupler. The power of the signal is adjusted by an optical variable attenuator (ATT) to suppress fluctuations in the output power of the ring circuit, which seem to be due to the transient gain of the optical amplifier in the circuit. The signal is modu-

lated into a pulse sequence $6 \mu\text{s}$ in width and with a period of $600 \mu\text{s}$ by the first AO pulse modulator, and the signal pulse is launched into the ring circuit. An erbium-doped fiber amplifier (EDFA) pumped by $1.48\text{-}\mu\text{m}$ laser diodes is used as the optical amplifier. Amplified spontaneous emission noise in the EDFA is reduced by a 1-nm bandpass filter (BPF). A delay line fiber is inserted, and the loop length is adjusted to $\sim 1.2 \text{ km}$, which corresponds to the pulse width of $6 \mu\text{s}$. The frequency shift of the AO frequency shifter incorporated in the ring circuit is $+80 \text{ MHz}$.

The cw-like output of the ring circuit is divided into two parts with a fiber coupler. One part is directed to a photodiode (PD), and the output profile is monitored. The other part is modulated into a pulse again by the second AO pulse modulator, in which the pulse width is adjusted so that it is the same as that of the input pulse. The second AO pulse modu-

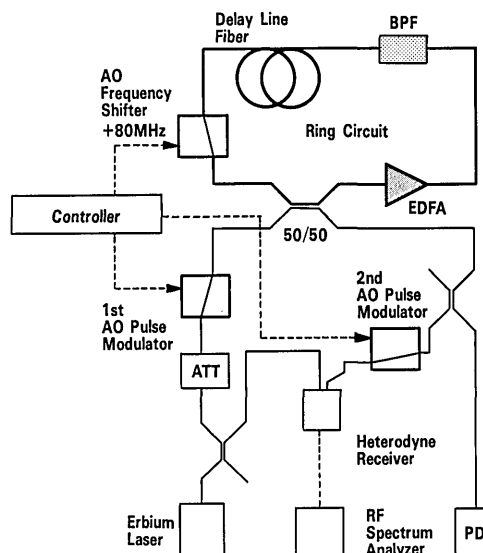


Fig. 2. Experimental configuration of the frequency translator and the setup for frequency shift measurements.

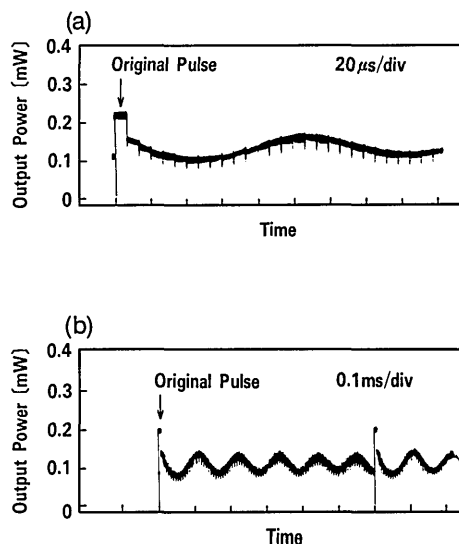


Fig. 3. Cw output profiles of the ring circuit; the pulse width is $6 \mu\text{s}$, and the period is $600 \mu\text{s}$. (a) Initial section of the output profile, (b) the whole cw output profile.

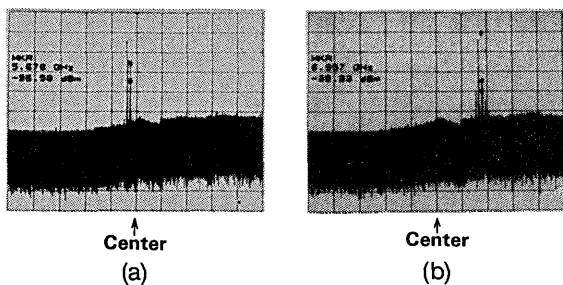


Fig. 4. Frequency shift measured on an rf spectrum analyzer; the center frequency is 5.84 GHz and the horizontal scale is 620 MHz/division. (a) Frequency shift of 5.68 GHz for a circulation number of 71, (b) frequency shift of 6.96 GHz for a circulation number of 87.

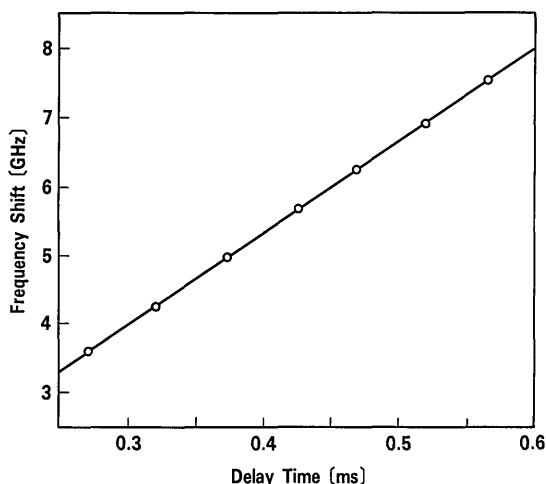


Fig. 5. Relationship between frequency shift and time.

lator is also synchronously controlled with the first AO pulse modulator with some delay time. A recirculated pulse with any frequency shift from the original pulse can be selected by adjusting the delay time. The selected pulse is directed to a heterodyne receiver, in which the reference light wave from the erbium laser is used as local optical power. The frequency shift of the selected recirculated pulse with respect to the reference light wave is measured with a frequency resolution of 3 MHz by an rf spectrum analyzer connected to the receiver. Here it should be noted that frequency shifts that are due to the first and second AO modulators offset each other.

Figures 3(a) and 3(b) show the initial section and the whole cw-like output profile from the optical ring circuit, respectively. Here the first pulse in Fig. 3(a) is the original pulse, and others are recirculated pulses. As shown in Fig. 3(b), the output power is stabilized over a period of 600 μ s, and its fluctuations are suppressed within $\sim 30\%$ of its averaged power. Here no exponential attenuation or amplification of the optical power is observed, hence approximate balance is achieved between the amplification gain and the loss of the ring circuit because of the gain saturation effect of the amplifier. Since the fluctuation amplitude depends on the input pulse power, the fluctuation seems to be related to the gain recovery of the amplifier.

The averaged output power monitored by the photodiode is approximately -10 dBm. The frequency shift of the selected recirculated pulse is clearly confirmed on the rf spectrum analyzer. Two examples are shown in Fig. 4(a), in which the frequency shift is 5.68 GHz, and in Fig. 4(b), in which the frequency shift is 6.96 GHz. The circulation numbers for Figs. 4(a) and 4(b) are estimated to be 71 and 87, respectively. Figure 5 shows the frequency shift of the recirculated pulse that is selected by the second AO modulator. All plotted points are on the same straight line within the accuracy of the received bandwidth of 3 MHz. Therefore it is confirmed directly that the optical frequency is translated over ~ 8 GHz, which corresponds to a circulation number of 100, with a strictly constant sweep rate with respect to time.

A strictly linear frequency translation can be achieved by this technique. However, the translation range is insufficient to apply to a tunable frequency standard for the coherent frequency-division-multiplexing systems, and the maximum circulation number of 100 is too small to be applied to C-OFDR. Therefore it is important to increase the circulation number so that this technique can be applied to many kinds of light-wave technology. In addition, suitable parameter values must be selected for each application. For example, the frequency shift at one circulation must be reduced to less than 10 kHz to reduce shot noise,³ and the loop length must be shortened to a spatial resolution for C-OFDR. Our further research will involve improving this proposed frequency translator with a view to its practical application.

In summary, we have proposed a new technique for the external frequency translation of light waves. This technique enables a strictly linear stepwise sweeping of light-wave frequency over a wide range. The frequency translator is composed of an optical pulse modulator and an optical ring circuit that contains an acousto-optic frequency shifter and an optical amplifier. The pulse launched into the ring circuit undergoes a constant frequency shift at every circulation around the circuit. We confirmed a frequency translation of as much as 8 GHz with a frequency step of 80 MHz.

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References

1. K. Nosu, H. Toba, and K. Iwashita, *IEEE J. Lightwave Technol.* **LT-5**, 1301 (1987).
2. K. Shimizu, T. Horiguchi, and Y. Koyamada, *IEEE Photon. Technol. Lett.* **3**, 1039 (1991).
3. K. Iizuka, Y. Imai, A. P. Freundorfer, R. James, R. Wong, and S. Fujii, in *Digest of Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, D.C., 1990), p. 460.
4. M. D. Levenson and S. S. Kano, *Introduction to Nonlinear Laser Spectroscopy* (Academic, San Diego, Calif., 1988).
5. P. L. Fuhr, D. N. Maynard, and D. L. Kunkel, *Proc. Soc. Photo-Opt. Instrum. Eng.* **1169**, 114 (1989).