# Stable Lightwave Frequency Synthesis Over 1-THz Span Using Fabry–Perot Cavity Containing Polarization-Rotation Elements and Actively Controlled Tunable Bandpass Filter

Hiroki Takesue, Fumihiko Yamamoto, and Tsuneo Horiguchi, *Senior Member, IEEE*

***Abstract*—We realized a lightwave synthesized frequency sweeper which has a $>1$-THz sweep span and operates stably. We employed an actively controlled tunable bandpass filter together with a Fabry–Perot cavity which consisted of a Faraday rotator mirror and a polarization rotation mirror. We confirmed that the frequency information of an input pulse was preserved after 1000 round-trips in the cavity and that signal pulses could circulate stably for 12 h.**

***Index Terms*—Acoustooptic switches, birefringence, Faraday effect, optical fiber amplifiers, optical fiber communication, polarization, wavelength division multiplexing.**

## I. INTRODUCTION

ENSE wavelength-division multiplexing (DWDM) networks have been developed intensively in recent years [1]. Optical spectrum analyzers (OSA) are currently used to identify wavelengths of optical paths in many such networks. Most practical OSA's employ lightwave frequency references which are tuned by mechanical movement (for example, diffraction gratings, tunable filters). As a result, the accuracy of optical frequency measurements using such OSA's is limited by the reliability of the mechanical moving parts and is typically of the order of a few gigahertz. As the wavelength channel spacing of DWDM networks becomes narrower, more accurate lightwave frequency references will possibly be needed.

One promising candidate is the lightwave synthesized frequency sweeper (LSFS), which generates time domain multiplexed frequency references [2]–[4]. The continuous lightwave from a frequency-stabilized master laser is modulated into an optical pulse and launched into a fiber-optic ring which contains an erbium doped fiber amplifier (EDFA), an acoustooptic frequency shifter (AOS), an optical coupler, an optical delay line (DL) and an optical bandpass filter (BPF). The optical loss that the pulse experiences is compensated for by the EDFA so the pulse can circulate many times around the ring. The pulse experiences successive frequency shifts while circulating so we obtain an optical pulse train whose frequency is swept stepwise. The fluctuation in the AOS frequency shift is very small compared with that of the master laser output, so each output pulse can be used as a lightwave frequency reference with almost the same accuracy as the master laser, which is typically <10 MHz. This is far better than the accuracy of the lightwave frequency references of conventional OSA's.

We reported an LSFS with a >1-THz sweep span which employs an actively-controlled tunable BPF (TBPF) [5]. The transmission peak frequency of the filter is controlled so that it tracks the frequency of a circulating pulse. As a result, the amplified spontaneous emission (ASE) noise arising from the erbium-doped fiber amplifier (EDFA) is eliminated effectively and the number of pulse circulations increases. However, the long-term stability of the frequency sweep has not yet been achieved because a small amount of polarization dependent loss (PDL) and fluctuation in the ring birefringence causes a cross-gain saturation (XGS) effect between the two polarization eigenmodes of the cavity, which often results in a serious decrease in the number of pulse circulations. Therefore, it has been difficult to use the LSFS in practice.

In this letter, we report an LSFS with a >1-THz sweep span which can operate stably. In addition to the actively-controlled TBPF, we employed a Fabry–Perot (FP) cavity which contains polarization-rotation elements so that the effects of the PDL and birefringence fluctuation were eliminated [6], [7]. We constructed the FP cavity with a Faraday rotator mirror (FRM) and a polarization rotation mirror (PRM) [8] and confirmed that the frequency information of an input pulse was preserved after 1000 round-trips in the cavity and that the pulses could circulate stably for 12 h.

## II. CONFIGURATION

Fig. 1 shows the configuration of our LSFS. First, we describe the PRM which is composed of a polarization beam splitter (PBS), an AOS with a –1-GHz frequency shift, and polarization-maintaining fibers (PMF). The PBS has three ports, A, B and C, as shown in Fig. 1. When a lightwave with an arbitrary state of polarization (SOP) is input into port A, a horizontally polarized wave (H wave) and a vertically polarized wave (V wave) are output from ports B and C, respectively. PMF's are connected to ports B and C so that the electric field vectors of the output lightwaves are aligned with one principal axis of the fibers. The PMF from port B is twisted by 90° at point D and connected to an AOS whose diffraction efficiency is maximum

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The authors are with NTT Access Network Service Systems Laboratories, Tsukuba, Ibaraki-ken 305-0805, Japan.

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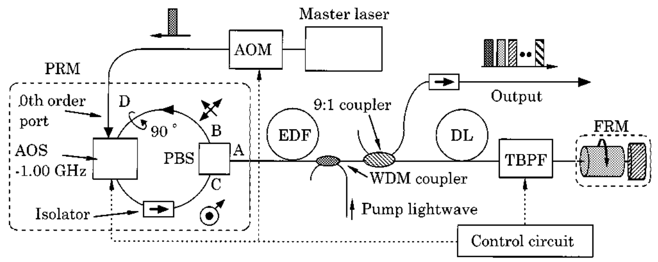


Fig. 1. Experimental LSFS configuration.

for V-wave input. The lightwave diffracted by the AOS is coupled to the PMF from port C. With this PRM, an H wave input from port A is output from port B, converted into a V wave at point D, frequency shifted by the AOS, and input into port C. As a result, a V wave with –1-GHz frequency shift is output from port A. Similarly, when a V wave is input, an H wave with –1-GHz shift is output. We constructed an FP cavity using this PRM and an FRM. The FRM also changes the input lightwave SOP to the orthogonal state. The SOP's of the lightwaves which propagate in the right and the left directions are orthogonal to each other at any point on the lightpath between the PBS and the FRM. Therefore, the effects of the PDL and birefringence on the path are canceled out and no PDL-related instability occurs.

However, when the polarization rotation angles of the FRM and PRM deviate from 90°, a small amount of PDL remains in the cavity and the XGS effect can occur between polarization modes. Therefore, we insert an isolator in the PRM, which only allows a lightwave propagating from port B to port C to pass. This means that only a V wave can be output from the PRM. As a result, the FP cavity has only one polarization eigenvalue which is not zero, and so the XGS effect between polarization modes is suppressed.

The FP cavity has a bidirectional EDFA, a 9 : 1 coupler, a DL and a TBPF between the PRM and the FRM. The continuous output from the master laser with a wavelength of 1539.310 nm is modulated into an optical pulse with an acoustooptic modulator (AOM). The SOP of the pulse is adjusted so that it becomes a V wave and the pulse is then input into the FP cavity through the 0th order port of the AOS. The pulse passes through the AOS and isolator before being input into port C of the PBS. The pulse output from port A is amplified at the EDFA and passes through the 9 : 1 coupler and DL. Then the pulse undergoes a spectral filtering at the TBPF to reduce the ASE level, and is reflected by the FRM while its SOP is rotated by 90°. The pulse retraces the same optical path and reaches port A. Here, the pulse should be an H wave because the effects of both the PDL and birefringence of the path between the PBS and the FRM are eliminated thanks to the polarization rotation of the FRM. Therefore, the pulse proceeds from port A to port B, and finally reaches the AOS again where it experiences a –1-GHz frequency shift. The pulse traces the route described above in each round-trip. The round-trip time in the cavity is 3.1 μs. The center frequency of the TBPF, whose 3-dB bandwidth is 1.4 nm, is swept from 1522 to 1595 nm so that it traces the frequency of the circulating signal pulse. Whenever the pulse passes through the 9 : 1 coupler from left to right, part of the energy is output from the coupler. Consequently, we obtain an optical pulse train whose frequency is swept in 1-GHz steps. The AOM, AOS and TBPF are synchronously controlled by a control circuit to realize repetitive generations of pulse trains.

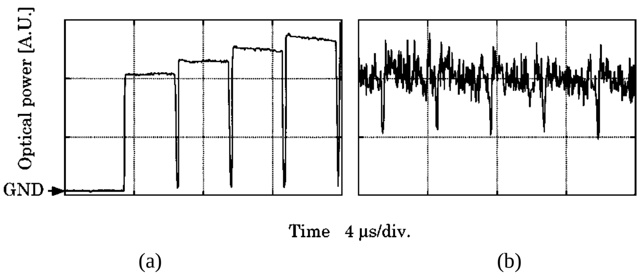


Fig. 2. Monitored optical pulse train around (a) 0th pulse and (b) 1000th pulse.

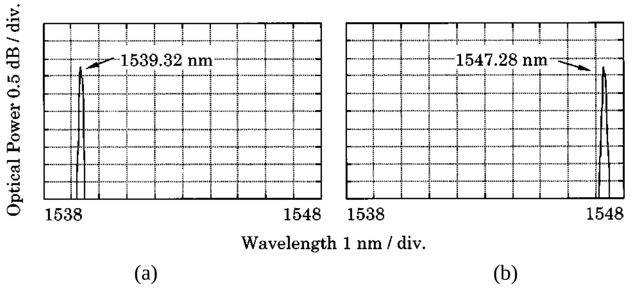


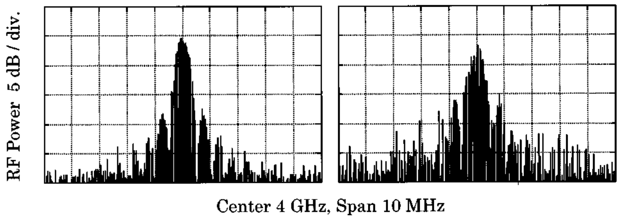
Fig. 3. Wavelength spectra of (a) 1st pulse and (b) 1000th pulse.

## III. EXPERIMENTS

Fig. 2 shows the monitored output pulse train around (a) the 0th and (b) the 1000th circulation. The pulse width was set about 100 ns shorter than the round-trip and 100 ns is far shorter than the relaxation time of the erbium ions in the EDFA. Therefore, we were able to monitor the level of the ASE noise arising from the EDFA at these 100-ns slots. The ratio of total power to ASE noise power ($R$) was approximately 2.0 at the 1000th pulse. We defined the number of pulse circulations as the number at which $R$ reached 1.5. The number was approximately 1100 in our experiment.

We confirmed the wavelength shift of the pulse. We extracted the 1st pulse (–1-GHz frequency shifted) and 1000th pulse (–1-THz frequency shifted) with another AOM placed at the output port, and measured their spectra using an OSA with a resolution bandwidth of 0.07 nm. The obtained spectra for the 1st and 1000th pulses are shown in Fig. 3(a) and (b), respectively. Thus, the wavelength shift was 7.96 nm which is in good agreement with the expected shift calculated from the circulation number.

With the previous experiment, we were not able to conclude that we had synthesized lightwave frequencies over a 1-THz span. This is because, without launching an optical pulse, this cavity works as a frequency shifted feedback fiber laser with resonant filtering [9] and can output a frequency-swept lightwave. Therefore, we checked to ensure that the initial frequency information of the input pulse was preserved after 1000 circulations with the following experiment. We applied a 4-GHz intensity modulation (IM) to the continuous output from the master laser. At the output, the 1st and 1000th pulses were extracted



(a) (b)

Fig. 4. RF spectra of (a) 1st pulse and (b) 1000th pulse.

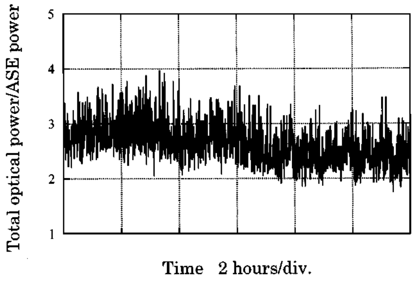


Fig. 5. Temporal change in ratio of total optical power to ASE power at 1000th pulse.

with an AOM, O/E converted, and monitored with an RF spectrum analyzer (RSA). The repetition rate of the extracted pulses was approximately 16 Hz. The resolution bandwidth and the sweep time of the RSA were set at 1 kHz and 25 s, respectively. Fig.4(a) is the RF spectrum of the first pulse, in which the 4-GHz component is clearly observed. Fig. 4(b) is that of the 1000th pulse. Though the sidelobes became blurred, the 4-GHz component can still be seen. This means that the IM sideband of the input pulse had been retained after 1000 successive frequency shifts and amplifications in the cavity. Thus, we confirmed that our LSFS successfully synthesized lightwave frequencies with a 1-THz span.

Finally, we observed $R$ of the 1000th pulse for 12 h to confirm the long-term stability of the pulse circulations. From the result shown in Fig. 5, $R$ had an average value of 2.6 and was always $>1.7$, which means that we were able to use this pulse as a frequency reference for at least 12 h. The fluctuations seen on the curve were probably caused by the timing jitter of the control circuit and can be eliminated by improving this.

## IV. CONCLUSION

We realized an LSFS with a 1-THz sweep span, which can operate stably by employing an actively-controlled TBPF together with an FP cavity that consisted of an FRM and a PRM. We confirmed that the frequency information of an input pulse was preserved after 1000 round-trips in the cavity and that the LSFS operated stably for 12 h.

We expect that this LSFS will be used for various applications including wavelength path identification in DWDM systems and the fast and highly accurate spectrometry of DWDM components.

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## REFERENCES

[1] H. Yoshimura, K. Sato, and N. Takachio, “Future photonic transport networks based on WDM technologies,” *IEEE Commun. Mag.*, vol. 37, pp. 74–81, Feb. 1999.
[2] T. G. Hodgkinson and P. Coppin, “Pulsed operation of an optical feedback frequency synthesizer,” *Electron. Lett.*, vol. 26, no. 15, pp. 1155–1157, 1990.
[3] K. Shimizu, T. Horiguchi, and Y. Koyamada, “Technique for translating light-wave frequency by using an optical ring circuit containing a frequency shifter,” *Opt. Lett.*, vol. 17, no. 18, pp. 1307–1309, 1992.
[4] K. Aida, J. Nakajima, and K. Nakagawa, “Synthesis of optical pulsed sweep frequencies from a fiber loop with automatic gain controlled erbium-doped fiber amplifier and AOD,” presented at the Eur. Conf. Optical Communications (ECOC’92), 1992, paper We A10.3.
[5] H. Takesue, F. Yamamoto, K. Shimizu, and T. Horiguchi, “1 THz lightwave synthesized frequency sweeper with synchronously tuned bandpass filter,” *Electron. Lett.*, vol. 34, no. 15, pp. 1507–1508, 1998.
[6] H. Sabert and E. Brinkmeyer, “Passive birefringence compensation in a frequency comb generator based on a linear fiber optical delay line,” *Electron. Lett.*, vol. 30, no. 10, pp. 812–814, 1994.
[7] H. Takesue, F. Yamamoto, and T. Horiguchi, “Stable lightwave synthesized frequency sweeper for the 1.5 μm band,” presented at the Eur. Conf. Optical Communications (ECOC’98), paper WdA33.
[8] T. Morioka, H. Takara, K. Mori, and M. Saruwatari, “Ultrafast reflective optical Kerr demultiplexer using polarization rotation mirror,” *Electron. Lett.*, vol. 28, no. 6, pp. 521–522, 1992.
[9] S. H. Yun, D. J. Richardson, D. O. Culverhouse, and B. Y. Kim, “Wavelength-swept fiber laser with frequency shifted feedback,” presented at the Conf. Optical Fiber Communications (OFC’97), paper TuH3.