Simple synchronization technique of a mode-locked laser for Laser-Compton scattering γ-ray source

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We propose a simple and effective synchronization technique between a reference electrical oscillator and a mode-locked laser for a narrowband picosecond Laser-Compton scattering γ-ray source by using a commercial-based 1-chip frequency synthesizer, which is widely used in radio communication. The mode-locked laser has been successfully synchronized in time with a jitter of 180 fs rms for 10 Hz - 100 kHz bandwidth. A good stability of 640 μHz at 80 MHz repetition rate for 10 hours operation has also been confirmed. We discuss in detail the design and performance of this technique (in terms of timing jitter, stability, and validity).

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I. INTRODUCTION

The development of laser-Compton scattering γ-ray (LCS-γ) sources with a combination of a laser system and a conventional electron accelerator has been progressing[1–5]. γ-ray beams can be used as a probe to detect an isotope of interest with nuclear resonance fluorescence (NRF)[6–8]. A conceptual design of the detection system for nondestructive assay of Pu and minor actinides have been proposed[8]. Numerical simulation has been performed to estimate the ^{239}Pu component whose fraction is 1% in the spent Boiling Water Reactor (BWR) nuclear fuel assembly consisting of 8×8 nuclear fuel rods. Results of the simulation calculation imply that stastical accuracy lower than 2% is possible with photons of 10^9 per second and 4000 sec measurement time. To generate such γ-rays, high-power narrowband laser pulses and high-current electron bunches are necessary to maintain higher photon flux. Moreover, synchronization between the laser beam and electron beam is also important. Contribution of timing jitter $\Delta\tau$ for degradation of the original γ-rays $N_{\gamma,0}$ can be obtained through discussion of luminosity[9]. For a Gaussian profile of a laser beam including timing jitter $\Delta\tau$ and a relativistic electron beam, we obtain

$$N_\gamma(\Delta\tau) = \eta(\Delta\tau) N_{\gamma,0}, \tag{1}$$

where

$$\eta(\Delta\tau) = \frac{1}{\sqrt{1 + \frac{c^2 \Delta\tau^2 \sin^2\phi}{(\sigma_{lx}^2+\sigma_{ex}^2)cos^2\phi + (\sigma_{lz}^2+\sigma_{ez}^2)sin^2\phi}}}. \tag{2}$$

Here (σ_{lx}, σ_{ly}, σ_{lz}) and (σ_{ex}, σ_{ey}, σ_{ez}) are the size of the laser beam and the electron beam in the (x_l, y_l, z_l) and the (x_e, y_e, z_e) directions (see in Fig. 1). c is the speed of light. The laser beam and electron beam propagate in the z_l and z_e direction, respectively. The two rectangular coordinate systems (x_l,y_l,z_l) and (x_e,y_e,z_e) crossed in the x-z plane with an angle of 2ϕ. For $\sigma_{lx} = \sigma_{ex} = 30$ μm in root-mean-square (rms), $\sigma_{lz} = \sigma_{ez} = c\ t_p = 600$ μm in rms (pulse duration: $t_p = 2$ ps) and $\phi = 9^{\,o}$ which are the nominal design values of the LCS-γ, $\Delta\tau < 1$ ps is necessary to maintain efficient performance (i.e. $\eta(\Delta\tau) > 0.95$). Stabilization techniques of the repetition rate of the laser system and master clock oscillator have been proposed for a long time[10,11]. However, this techniques do not meet for such applications due to lower sensitivity or poor accuracy in the phase error (e.g. phase detection frequency and phase noise of the phase detector), directly. Recently, the synchronization technique has rapidly progressed for the x-ray free electron laser (XFEL). Timing jitter between a mode-locked Ti:Sapphire laser pulse and the x-ray pulse is 120 fs root-mean-squared deviation (RMS)[12,13]. This technique uses frequency multiplying of the laser repetition rate for amplification of the phase error. In the Lineac Coherent Light Source (LCLS), the 42th ($\times 7$ at a photo diode and $\times 6$ at a multiplier) harmonic is used[13]. More recently, phase error detection with attosecond resolution by using optical cross correlation[14,15] has been proposed and applied at Deuches Elektronen-Synchrotron (DESY)[16] and SwissFEL[17]. In both cases, precise detection of the phase error is performed by linking of modules. In particular, the development of an integral circuit (IC) device for radio communication has remarkably progressed[18]. It provides high performance of ultra-low phase noise for radio communication. However, to date, there are no reports of the combination of this advanced IC device and short pulses laser for synchronization. If it is possible to apply this advanced technology to laser development, it would be possible to construct a simple and conveniently high-performance system. In this work, we report on a simple synchronization technique for a mode-locked laser with a 1-chip frequency synthesizer, which is widely used for radio communication. The experimental result fits well with a theoretical model of the phase-locked-loop (PLL) based on radio communication.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 2(a) shows a typical block diagram of a PLL, which is widely employed in electronic applications such as radio communication[19,20]. The PLL generates an output signal whose phase is related to the phase of an input "master" signal. It is an electronic circuit consisting of a reference oscillator, a voltage control oscillator (VCO), a phase frequency detector (PFD), a gain amplifier, and a feedback divider. The frequency is controlled by the error signal and is stabilized by repeating this loop. The cut-off frequency of the low-pass filter is related to the repetition rate of the stabilization procedure. Here, the phase locked loop can be analyzed as a negative-feed back system with a forward gain term and a feedback term in the frequency domain. Figure 2(b) shows the main phase noise contributors in a PLL. The output phase noise $S_{\phi_o}(s)$ in the frequency domain, which is equivalent to the timing jitter in the time domain can be described as

$$S_{\phi_o}(s) = S_{\phi_v}(s) \mid \frac{1}{1+G(s)H(s)} \mid^2 + S_{\phi_r}(s) \mid \frac{G(s)}{1+G(s)H(s)} \mid^2, [s = j\omega = j2\pi f]. \quad (3)$$

where $S_{\phi_v}(s)$ is the phase noise of the voltage control oscillator, $S_{\phi_r}(s)$ is the phase noise of the reference at the PFD, $H(s)$ is the feedback transfer function at the feedback divider, $G(s)$ is the forward gain at the gain amplifier, and f is the offset frequency.

Here, an electromechanical device such as lead zironate titanate (PZT) can convert an electrical signal to a mechanical displacement. By installing such device into the laser cavity, the mode-locked laser repetition rate f_{rep} = c/2L (here, c is the speed of light and L is the cavity length between the end-mirrors) can be varied by changing the applied voltage, and this component can be treated as a VCO. Therefore, the basic design of the repetition rate control in a mode-locked laser system can be treated as the above block diagram. In addition, the theoretical phase noise of the repetition rate with stabilization is also obtained in the above equation.

Figure 3(a) shows a schematic view of the experimental setup and the block diagram of developed repetition rate stabilization equipment. In the experiment, a mode-locked Ti:Sapphire laser was used. The laser system provides 86 MHz repetition rate, 840 nm center wavelength, 15 nm spectrum band-width in full-width-half-maximum, and 200 mW output power. The output of the laser pulse was converted to an electric signal by a fast p-i-n photo-diode (DET10A/M, Thorlabs Co.Ltd.). This signal was band-pass filtered (f_{BPF} = 83$\pm$7 MHz) and amplified to detect the laser repetition rate. The filtered signal was input into a 1-chip frequency synthesizer (ADF4002, Analog Devices Co.Ltd)[18] in a test circuit (see in Fig. 3(b)). This frequency synthesizer is composed of limit amplifiers, frequency dividers for the reference channel and the source channel, and the phase error detector (see in Fig. 4). The output signal from the phase error detector fed into an external loop filter in the test circuit. In order to simplify the theoretical consideration, a passive 2nd order low-pass filter was used in the experiment. The passive 2nd order low-pass filter was composed of a 1st order low-pass filter C_2R_2 with time constant of $T_2 = C_2R_2$ and a capacitor C_1 for relaxation of pattern jitter with time constant of $T_2 = C_2R_2$. The low-pass filtered signal was buffered by a OP-AMP (LF412, Texas Instruments) in the test circuit and fed into an external PZT driver (M-2654, Mess-tek Co.ltd). The PZT driver provided a control signal to a PZT actuator (AE0203D04F, NEC tokin Co.Ltd), which was installed into the Ti:Sapphire mode-locked laser cavity. The phase noise of the laser pulse was obtained by another PD (DET10A/M, Thorlabs Co.Ltd.). The phase noise of the laser repetition rate signal was analyzed by the signal source analyzer (E5052A, Agilent Co.Ltd.).

The experimentally obtained phase noise is shown in Fig. 5. The phase noise of the mode-locked laser pulses for the free running and reference signal are also plotted. We observed improvement of phase noise by the PLL in the lower frequency component. Here, the theoretical phase noise from the control model can be evaluated by using Eq. (3). To discuss the theoretical phase noise in more detail, the forward gain G(s) and feed back divider gain H(s) should be obtained by an appropriate model. Figure 6 shows the basic PLL model for consideration in our experiment. The feedback transfer function $H(s) = 1/N$ and the forward transfer function $G(s) = K_pF(s)K_v/s$ can be obtained. Here, K_p is the phase characteristic at phase error detector, $F(s)$ is the transfer function at the loop filter, and K_v is the slope of the oscillator frequency to voltage characteristic. Substituting for $H(s)$ and $G(s)$ in Eq. (3), we have

$$S_{\phi_o}(s) = S_{\phi_v}(s) \mid \frac{Ns}{Ns + K_pK_vF(s)} \mid^2 + S_{\phi_r}(s) \mid \frac{NK_pK_vF(s)}{Ns + K_pK_vF(s)} \mid^2 . \tag{4}$$

In the experiment, the frequency divider for the source channel and the phase characteristic at the phase error detector were set at $N = 2$ (i.e. phase comparator frequency: 43 MHz) and $K_P = I_{pump}/2\pi = 3.5 \times 10^{-4}$ A/rad, respectively where I_{pump} was the maximum charge pump current at the PFD. The slope of the oscillator frequency to voltage characteristic was $K_v = 1.9 \times 10^{2}$ rad/V. The transfer function of the loop filter $F(s)$ can be determined by the ratio between the output voltage and the input current. Then,

$$F(s) = \frac{1 + sT_2}{A_1 s + A_0} \tag{5}$$

where, $T_2 = C_2R_2$, $A_0 = C_1 + C_2$, and $A_1 = C_1C_2R_2$. In the experiment, we choose $C_1 =$ 1.2 nF, $C_2 = 150$ nF, and $R_2 = 13$ kΩ. Therefore, the time constant of the low-pass filter is $T_2 = 2.0$ ms (or equivalently a 500 Hz cut off frequency). We confirmed that the predicted phase noise is reasonable compared with the experimental result. Here, the timing jitter, J, as a function of phase noise $S(f)$ can be described as

$$J = \frac{1}{2\pi f_{rep}} \sqrt{2 \int 10^{\frac{S(f)}{10}} df}. \tag{6}$$

Then, the timing jitters for 10 Hz to 100 kHz bandwidth were estimated to be 5 ps during free running and 180 fs during the PLL operation, respectively.

In particular, we measured the long-term stability of the cavity lock. Over more than 10 hours of hold time was confirmed by monitoring a frequency counter (53230A, Agilent Co.ltd.) (Fig. 7). The long-term laser cavity fluctuation is highly compensated by installing this equipment. Here, the stability of the repetition rate represented by the Allan standard deviation $\sigma_y(\tau)$ has been universally used to evaluate the stability of signal sources[21]. It is defined as

$$\sigma_y(\tau) = \sqrt{\frac{1}{2}\langle(\overline{y_{n+1}} - \overline{y_n})^2\rangle}, \tag{7}$$

where τ is the observation period, $\overline{y_n}$ is the n-th fractional frequency average over the observation time τ. The stability of the repetition rate was improved to 640 μHz at $\tau = 1$ sec for 10 hours laser operation. This result implies that the repetition rate of the mode-locked laser is strongly locked by stable signal processing in the PLL loop, and this system is sufficient for long time operation, which is typical as a laser operation time such as a high-power laser system.

III. SUMMARY

The technique of a simple repetition rate stabilization for a mode-locked laser by using a 1-chip frequency synthesizer was performed. The timing jitter was improved to 180 fs with this technique. Moreover, we compared the phase noise between the experimental result and model prediction based on the PLL theory for radio communication. The result of the model prediction was reasonable compared with the experimental results. This result shows that the timing stabilization of the mode-locked laser can be simplified including the design of an electric circuit. In addition, the cavity locking was strong. A long hold time (>10 hours) was observed. These experiments clearly demonstrate that our technique, with its good synchronization as well as being simple and inexpensive, is useful for NRF applications using LCS-γ rays(interaction between picosecond electron bunches and picosecond laser pulses).

ACKNOWLEDGMENTS

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REFERENCES

[1] H. Ohgaki et al., Nucl. Instr. and Meth. A **455**, 54 (2000).

[2] S. Kashiwagi et al., J. Appl. Phys. **98**, 123302 (2005).

[3] J. Pruet et al., J. Appl. Phys. **99**, 123102 (2006).

[4] K. Kawase et al., Nucl. Instr. and Meth. A **637**, S141 (2011).

[5] F. Albert et al., Phys. Plasmas **19**, 056701 (2012).

[6] W. Bertozzi and T. Gozani, Nucl. Instr. and Meth. B **241**, 820 (2005).

[7] R. Hajima et al., Nucl. Instrum. Meth. A **608**, S57 (2009).

[8] T. Hayakawa et al., Nucl. Instrum. Meth. A **621**, 695 (2010).

[9] T. Suzuki, KEK reports **KEK-76-3** (1976).

[10] M. J. W. Rodwell et al., IEEE J. Quantum Electron. **25**, 817 (1989).

[11] S. B. Darack et al., Opt. Lett. **16**, 1677 (1991).

[12] J. M. Glownia et al., Opt. Express **18**, 17620 (2010).

[13] J. M. Byrd et al., Proc. IPAC10, MOOCRA03 (2010).

[14] T. R. Schibli et al., Opt. Lett. **28**, 947 (2003).

[15] J. Kim et al., Opt. Lett. **32**, 3519 (2007).

[16] S. Schlz et al., Nature Comm. **6**, 5938 (2015).

[17] M. C. Divall et al., Opt. Express **23**, 29929 (2015).

[18] ADF4002 Data sheet, Analog devices Co. Ltd (2006).

[19] H. Komiya, Transistor Technology **43(4)**, 215 (2006) *(in Japanese)*.

[20] H. Komiya, Transistor Technology **45(1)**, 240 (2008) *(in Japanese)*.

[21] D. Allan, Proc. of IEEE, **54**, 221 (1966).

Figure captions

Fig. 1. Geometry of the crossing region.

Fig. 2. (a) Basic phase-locked-loop model. (b) Block diagram of PLL-phase-noise contributors.

Fig. 3. (a) Block diagram of the developed repetition rate stabilization equipment. A timing jitter of the laser pulse was obtained by using signal analyzer. (b) Photograph of the test circuit (effective size: 5x5cm). A CD(size:12cm) is on the left side for comparison.

Fig. 4. Block diagram of the 1-chip frequency synthesizer.

Fig. 5. Characteristic of the phase noise. The experimental result and prediction of the simple model are plotted.

Fig. 6. Block diagram of the basic PLL model for the prediction.

Fig. 7. Long-term stability of the laser repetition rate.

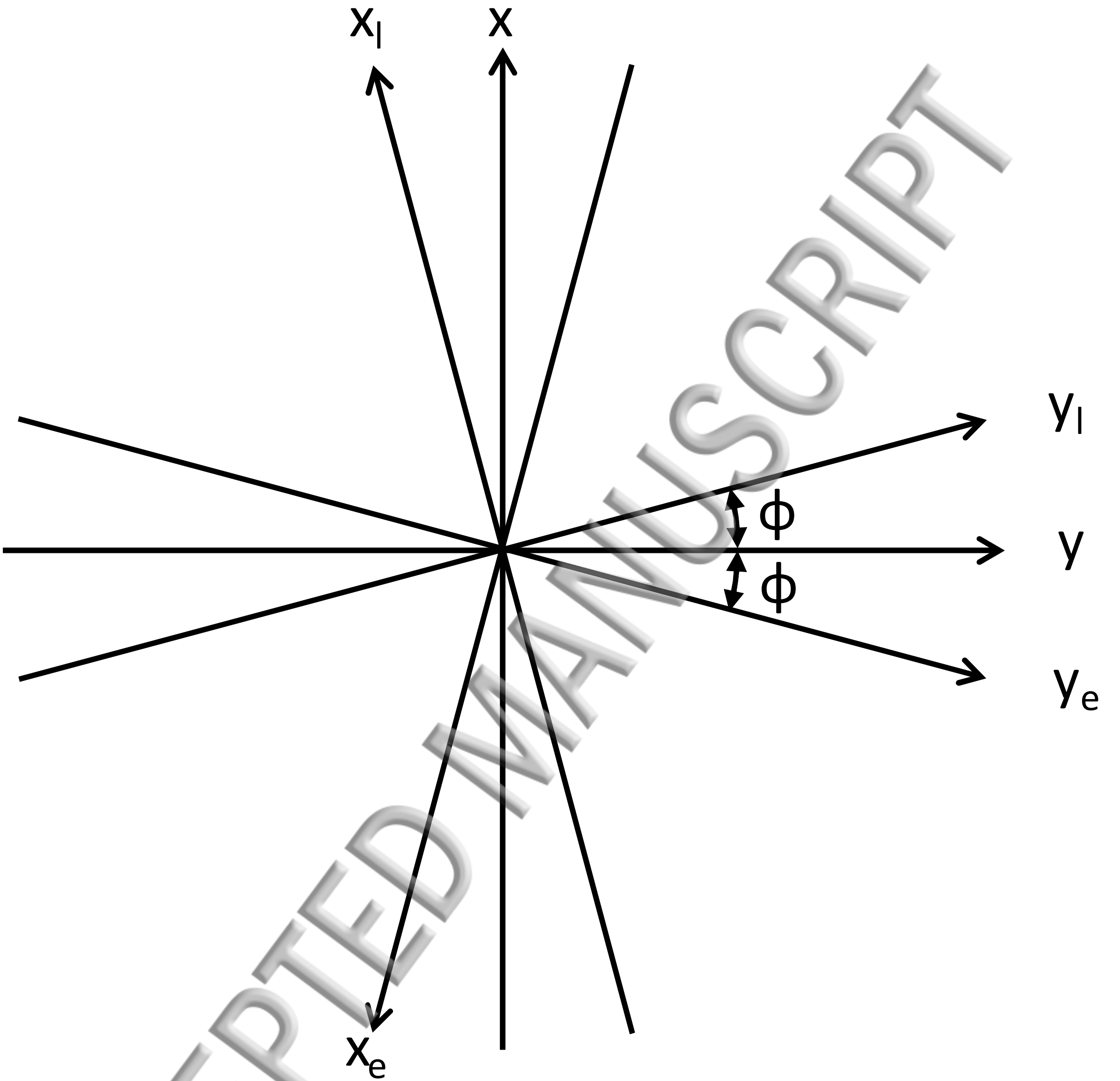


Fig.1 M MORI

(a)

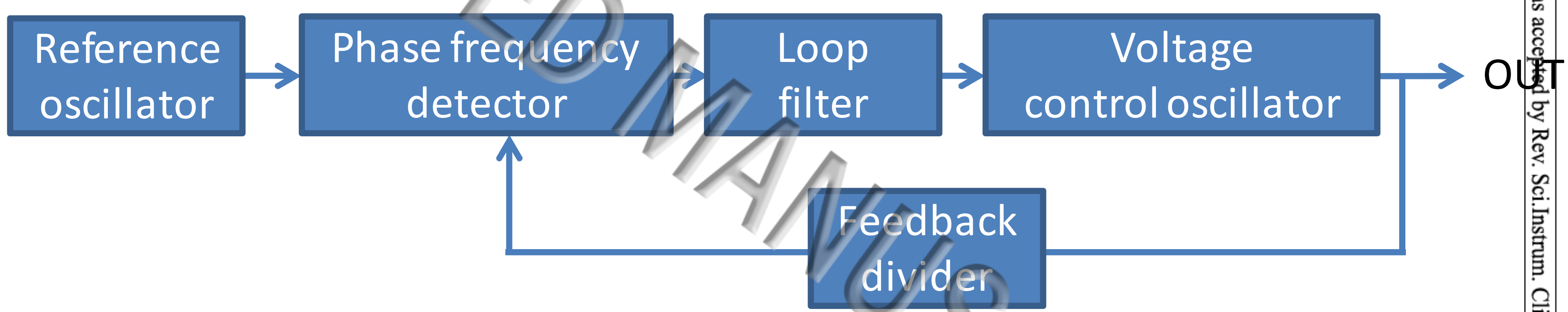


Fig.2(a) M MORI

(b)

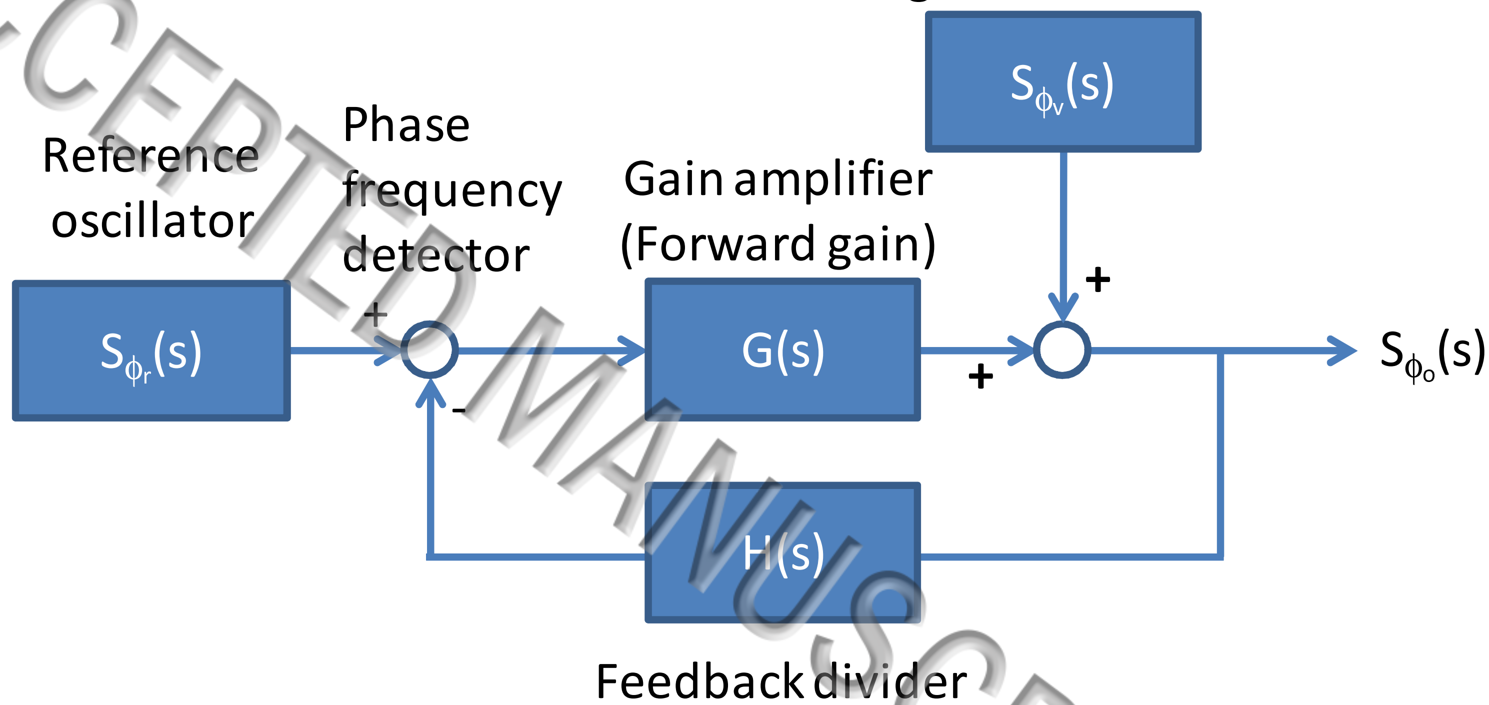


Fig.2(b) M MORI

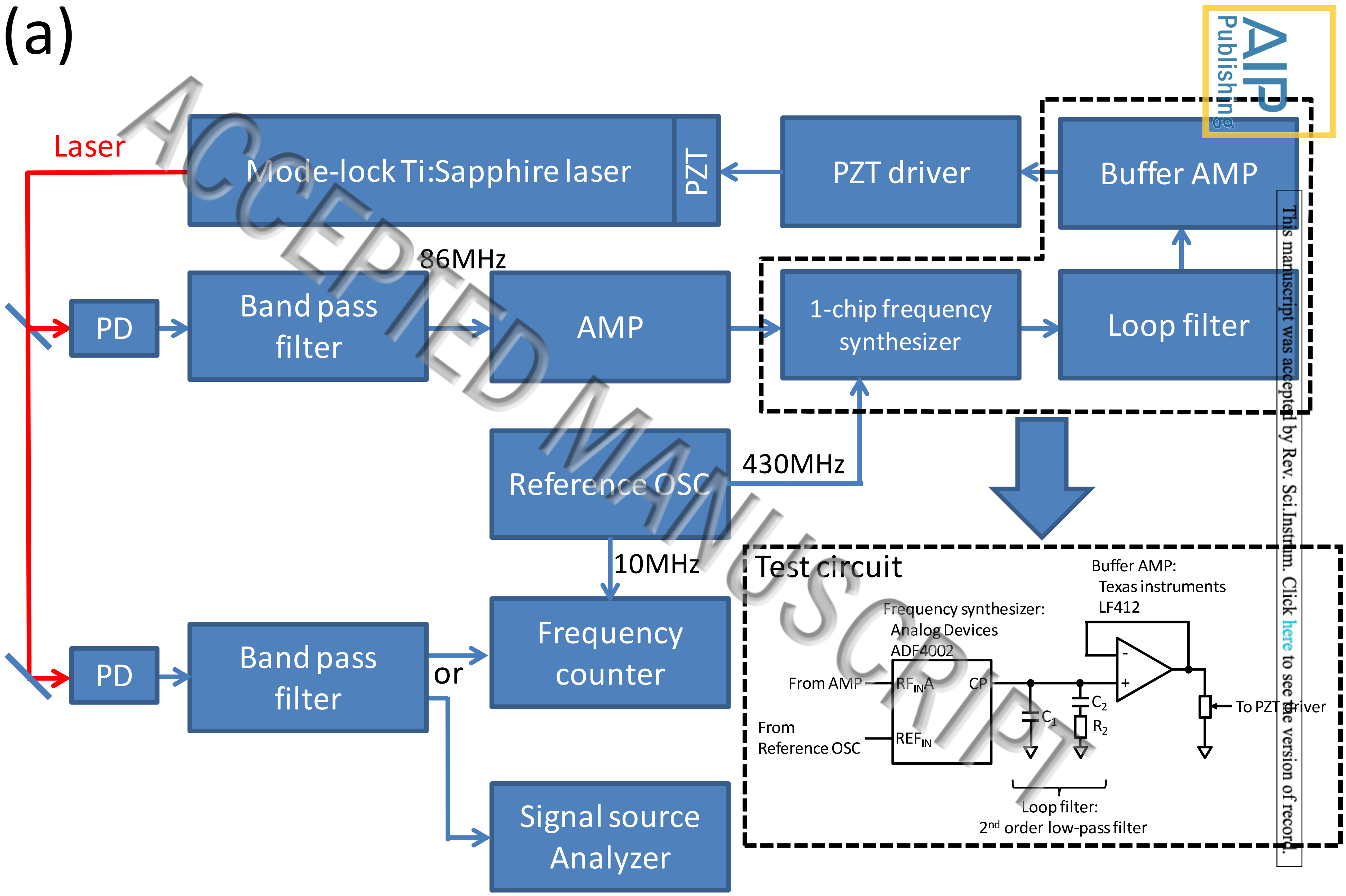
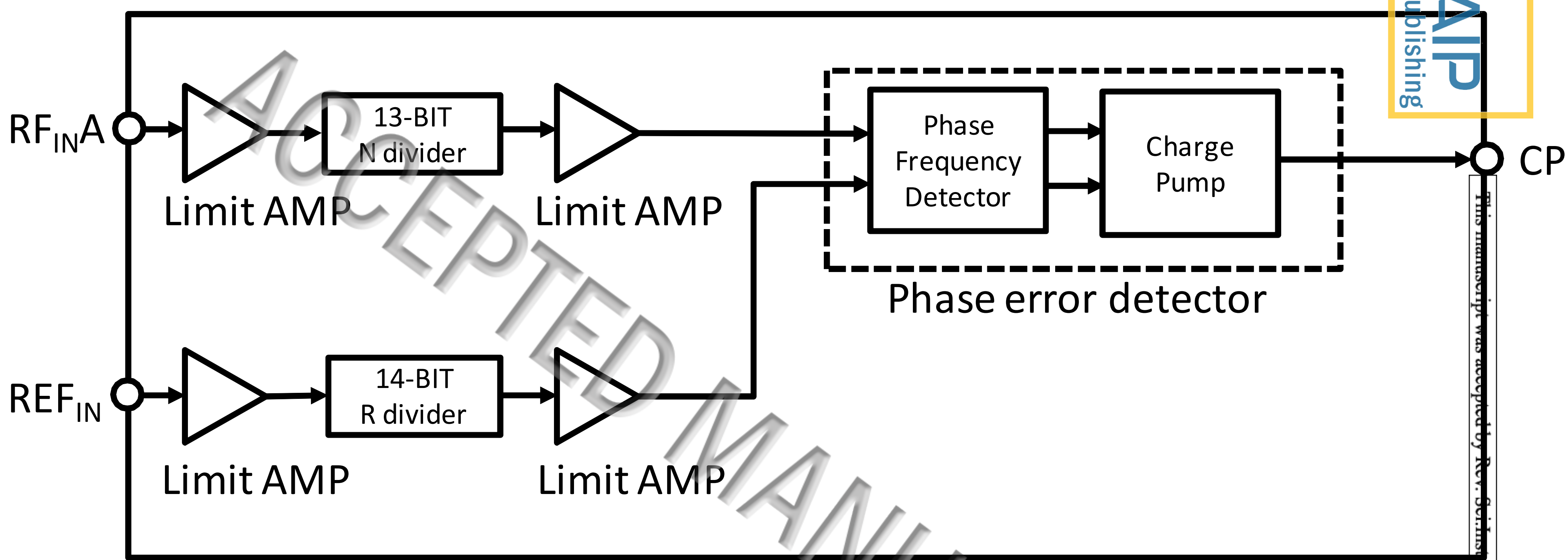

(a)
Laser
Mode-lock Ti:Sapphire laser
PZT
PZT driver
Buffer AMP
PD
Band pass filter
86MHz
AMP
1-chip frequency synthesizer
Loop filter
Reference OSC
430MHz
10MHz
PD
Band pass filter
or
Frequency counter
Signal source Analyzer
Test circuit
Frequency synthesizer: Analog Devices ADF4002
Buffer AMP: Texas instruments LF412
From AMP
From Reference OSC
RF_IN A
REF_IN
CP
C1
C2
R2
To PZT driver
Loop filter: 2nd order low-pass filter

Fig.3(a) M MORI

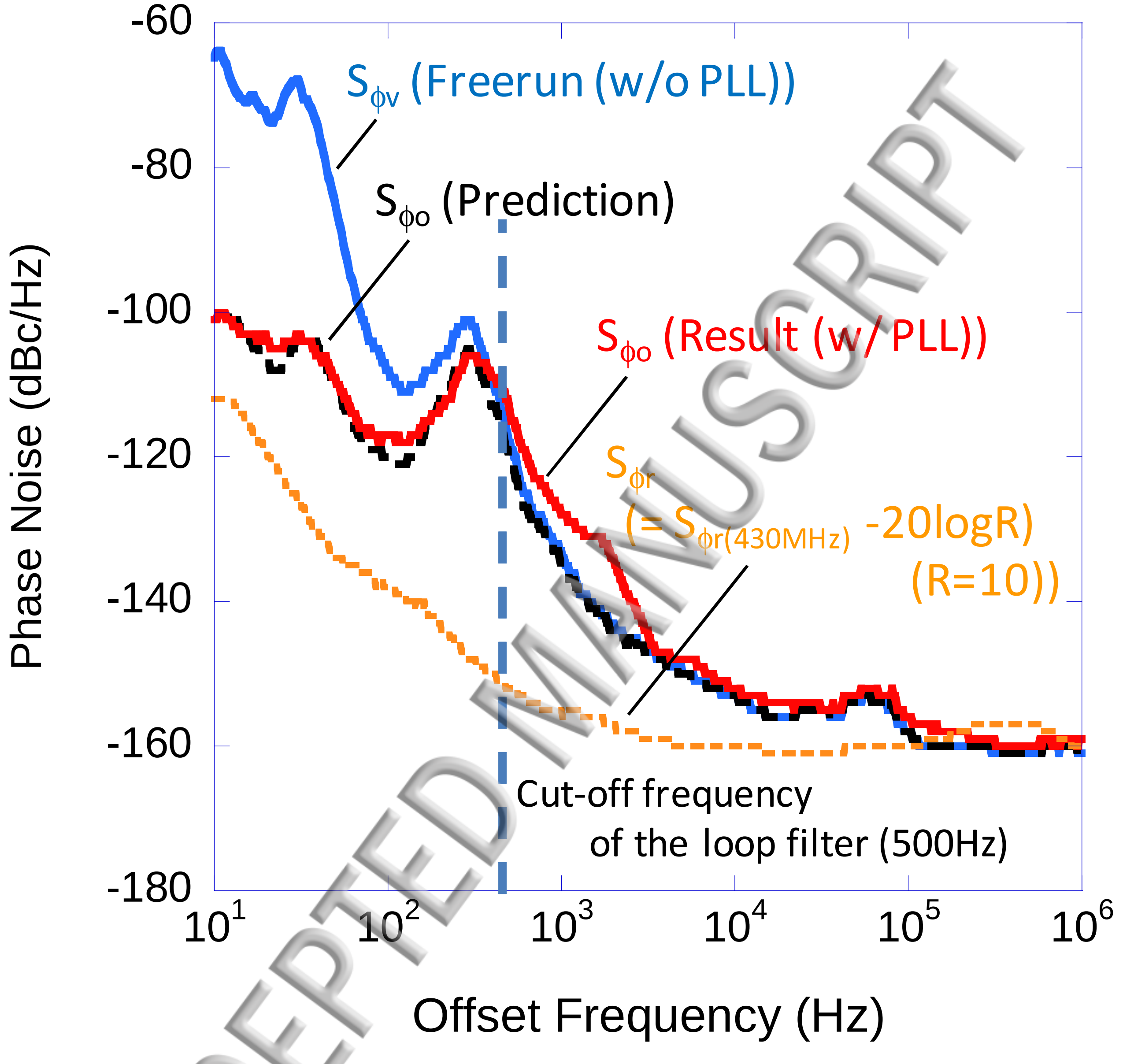
(b)

Fig.3(b) M MORI



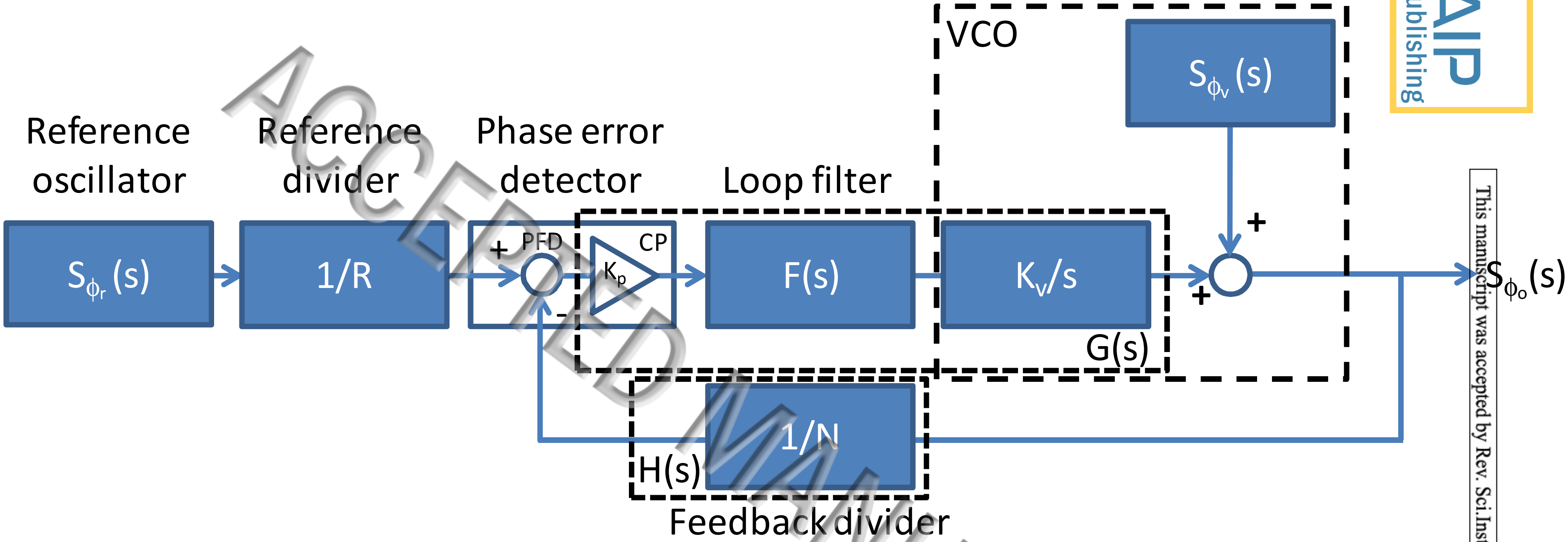
RF$_{IN}$A
REF$_{IN}$
Limit AMP
13-BIT
N divider
Limit AMP
Limit AMP
14-BIT
R divider
Limit AMP
Phase
Frequency
Detector
Charge
Pump
Phase error detector
CP

Fig.4 M MORI



-60
-80
-100
-120
-140
-160
-180
Phase Noise (dBc/Hz)
$S_{\phi v}$ (Freerun (w/o PLL))
$S_{\phi o}$ (Prediction)
$S_{\phi o}$ (Result (w/ PLL))
$S_{\phi r}$
(= $S_{\phi r(430MHz)}$ -20logR)
(R=10))
Cut-off frequency
of the loop filter (500Hz)
10^1
10^2
10^3
10^4
10^5
10^6
Offset Frequency (Hz)

Fig.5 M MORI



Reference oscillator
Reference divider
Phase error detector
Loop filter
VCO
$S_{\phi_v}(s)$
$S_{\phi_r}(s)$
1/R
PFD
CP
K_p
F(s)
K_v/s
G(s)
1/N
H(s)
Feedback divider
$S_{\phi_o}(s)$

Fig.6 M MORI

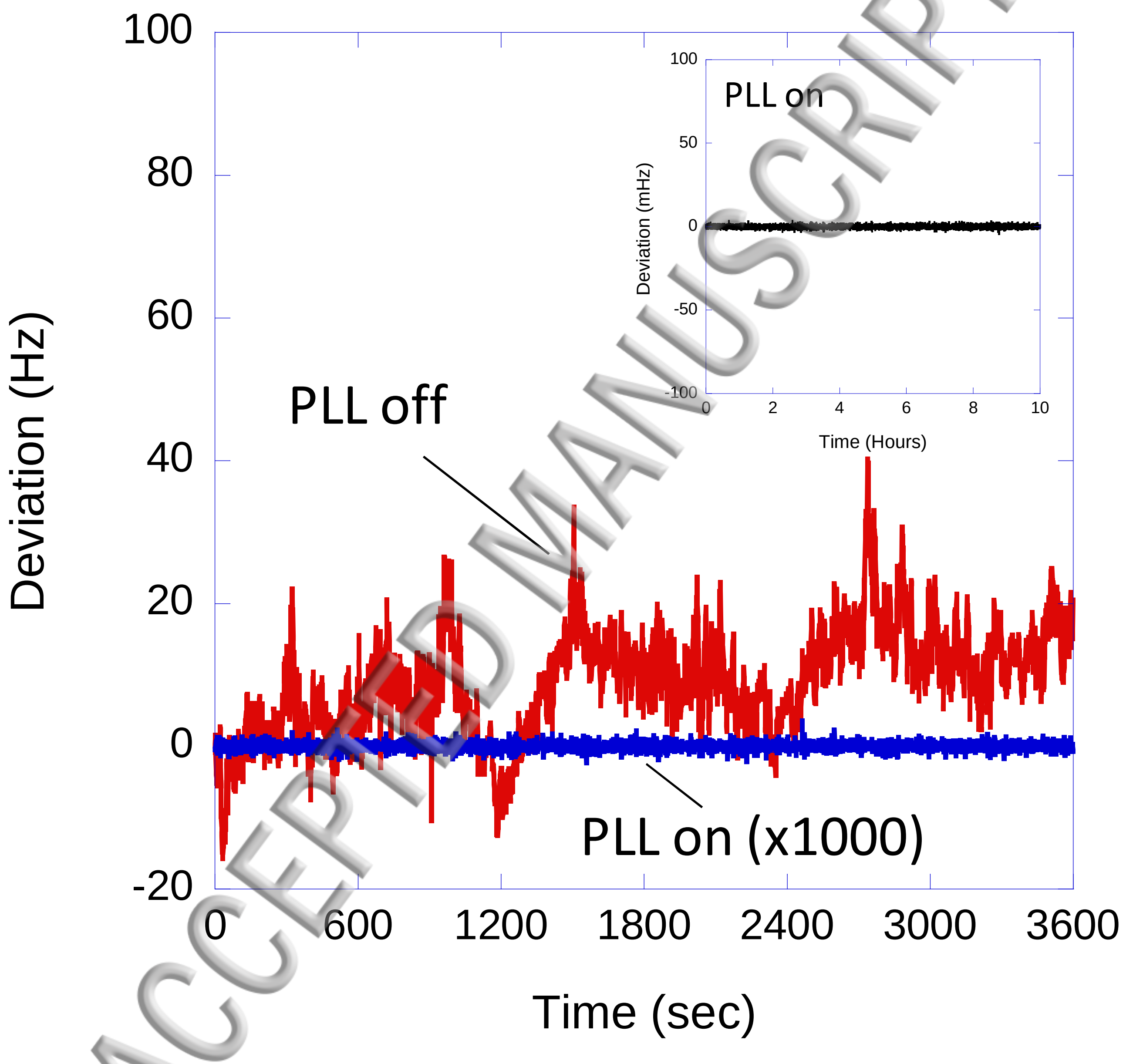

100
80
60
40
20
0
-20
Deviation (Hz)
0
600
1200
1800
2400
3000
3600
Time (sec)
PLL off
PLL on (x1000)
PLL on
Deviation (mHz)
Time (Hours)

Fig.7 M MORI