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Reflection-Type Delayed Self-Homodyne/Heterodyne Method for Optical Linewidth Measurements

Koichi Iiyama, Ken-ichi Hayashi, *Member, IEEE*, Yoshio Ida, Hitoshi Ikeda, and Yoshihisa Sakai

***Abstract*—The reflection-type delayed self-homodyne (RDSH) method described here is based on the same principle as the delayed self-homodyne/heterodyne (DSH) method but no beam splitter or fiber coupler is required. The delayed beam is produced by utilizing a round-trip propagation passing through a solitary long optical fiber delay line. Therefore, the optical configuration is very simple and the beat signal has a resolution twice that of the DSH method. However, the RDSH method has a drawback in that a large intensity difference between the two beams reduces the level of the beat signal. This can be improved by increasing the reflectivities of the fiber ends by dielectric coating. In this case multiple reflection at the fiber ends should be taken into account. Resultingly an improvement more than 12 dB is analytically predicted and is experimentally confirmed. Finally a heterodyning scheme of RDSH method is also presented.**

I. Introduction

SPECTRAL linewidth narrowing of semiconductor lasers (LD's) is required in coherent optical communications and optical measurement systems where LD's are used as light sources. For measuring such a narrowed spectral linewidth [1]–[4], a Fabry–Perot interferometer may not be used because of its poor resolution. Hence, the delayed self-homodyne/heterodyne (DSH) method [5] has been widely used. In this method the optical beam from an LD under test is divided into two beams, one of which is delayed in time with respect to the other by passing through a long single-mode optical fiber.

In the reflection-type delayed self-homodyne (RDSH) method [6] proposed previously by us, only a solitary long optical fiber delay line is required. In producing the beat signal the delayed beam is generated by utilizing reflection at both ends of the fiber. Since the round-trip delay time of the fiber is used, the resolution of the RDSH method is doubled as well. In Section II, the principle and resolution of the RDSH method is described both analytically and experimentally. In Section III, improvement of the best signal level by means of increased reflectivities of the fiber ends is discussed. In Section IV, a heterodyning scheme of RDSH method using an optical frequency-shifter module with fiber pigtails is described and its validity is demonstrated by using bulk-optic components.

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K. Iiyama, K. Hayashi, Y. Ida, and H. Ikeda are with the Department of Electrical and Computer Engineering, Faculty of Technology, Kanazawa University, Kodatsuno, Kanazawa-shi, 920, Japan.

Y. Sakai is with NTT Opto-electronics Laboratories, Atsugi-shi, kanagawa, 243-01, Japan.

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II. Demonstration of RDSH Method

A. Principle

In Fig. 1(a) a configuration of the RDSH method is described. The optical beam from an LD under test passes through an optical isolator (ISO) and is coupled into a single-mode optical fiber. A large part of the coupled beam emerges from its far end, and the rest goes back to the near end where a small part of it is reflected again. So the second beam emerging from the far end is delayed by a round-trip delay time of the fiber relative to the first emerging beam. Thus the multiple reflection repeats endlessly.

In case of a long optical fiber with a low reflectivity of cleaved fiber ends (normally 4% in power), only the first two beams dominate and are mixed on a wide-band photodetector (APD). In addition to the advantages of the DSH method, this configuration has the following excellent features.

1. (1) An extremely simple optical configuration is achieved.
2. (2) Since the optical fiber itself plays a role of a spatial filter, wavefront matching of the two beams is almost automatically accomplished.
3. (3) Because of the doubled delay time due to a round-trip propagation, the resolution is doubled as well.
4. (4) From the reasons described in (1) and (2) the beat signal is very stable against environmental perturbations.

On the other hand, it has a drawback in that a large intensity difference between the two beams reduces the best signal level. If the fiber end reflectivities are increased by means of dielectric coating, the beat signal level will be readily improved. The detail of this effect is described in the next section.

For the time being, let's consider only the first two beams. The optical fields of these two beams are denoted by the following:

$$E_0(t) = \sqrt{PA}(1 - R) \cos [\omega_o t + \phi(t)] \tag{1}$$

$$E_1(t) = \sqrt{PA}(1 - R) RA \cos [\omega_o(t - \tau_d) + \phi(t - \tau_d)] \tag{2}$$

where P is the optical power in front of the near end of the fiber, R is the optical power reflectivity of the fiber ends, A is the power transmittance of the fiber, τ_d =

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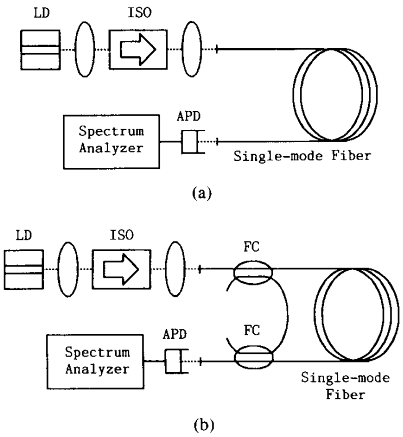

Fig. 1. (a) Configuration of RDSH (homodyne) method. (b) Configuration of DSH (homodyne) method. FC: 3 dB fiber coupler.

$2nL/c$ (n = refractive index of the fiber, L = fiber length, c = light velocity in vacuum) the round-trip delay time of the fiber, ω_o and $\phi(t)$ are the angular frequency and the phase fluctuation of the optical field, respectively. The beat signal detected by an APD is given as the form

$$I(t) = [E_0(t) + E_1(t)]^2 = P(1 - R)^2 RA^2 \cos [\omega_o \tau_d + \phi(t) - \phi(t - \tau_d)]. \quad (3)$$

In the second line of (3), dc and optical frequency terms are omitted. If $\phi(t)$ is assumed to be a Gaussian process and a random walk process, a procedure similar to that in a literature [7] leads us to the following spectral distribution:

$$S(\omega) = I_0^2 \frac{W}{\omega^2 + W^2} \cdot \left[1 - e^{-W\tau_d}\left\{\cos(\omega\tau_d) + \frac{W}{\omega}\sin(\omega\tau_d)\right\}\right] \quad (4)$$

where $I_0 = P(1 - R)RA^2$ and W is the linewidth of the LD. For the DSH method using two 3-dB fiber couplers and a fiber with a power transmittance A (see Fig. 1(b)), the spectral profile of the beat signal is given as [7]

$$S(\omega) = I_1^2 \frac{W}{\omega^2 + W^2} \cdot \left[1 - e^{-W\tau_o}\left\{\cos(\omega\tau_o) + \frac{W}{\omega}\sin(\omega\tau_o)\right\}\right] \quad (5)$$

where $I_1 = P\sqrt{A}/4$ and $\tau_o = \tau_d/2$ is a single path delay time of the fiber. Equations (4) and (5) have the same profile except for the proportionality constants (I_0 and I_1) and the delay times (τ_d and τ_o). It is found from these equations that the delay time of the RDSH method is doubled as compared with the corresponding DSH method having the same fiber length, so the doubled resolution is expected.

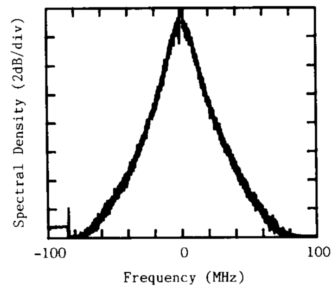

Fig. 2. Example of spectral profile of LD (CSP type, 0.83 μm, Hitachi HLP-1400, I/I_{th} = 1.79) measured by RDSH (homodyne) method.

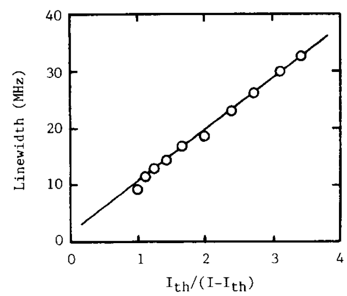

Fig. 3. Dependence of spectral linewidth on laser injection current measured by RDSH (homodyne) method.

For an LD (CSP type, 0.83 μm, Hitachi HLP-1400, I/I_{th} = 1.79; I = injection current, I_{th} = threshold current) the spectral profile of the beat signal is measured by the RDSH method using a single-mode optical fiber (6-μm core diameter and 100-m length) and is shown in Fig. 2. The spectrum has the Lorentzian profile with 13-MHz HWHM, which is the same as that obtained by the DSH (homodyne) method. The dependence of the spectral linewidth on the laser injection current is also measured by the RSDH method and is shown in Fig. 3. It is found that the spectral linewidth is inversely proportional to the injection current. This result agrees with that obtained by the DSH method.

B. Resolution

The improvement of the resolution by the RDSH method was confirmed by using an LD with 13-MHz linewidth and optical fibers of various lengths. Fig. 4 shows the beat signals measured by the RDSH method ((a), (c)) and by the DSH (heterodyne) method ((b), (d)). The fiber lengths are 5 m ((a), (b)) and 2.5 m ((c), (d)), respectively. For 5-m fiber length the spectra (a) and (b) are quite different. The spectrum (a) assumes nearly Lorentzian profile with 13-MHz HWHM, whereas spectrum (b) is almost the same profile as spectrum (c). These spectra are predicted from (4) and (5). Thus the doubled resolution of the RDSH method is experimentally confirmed.

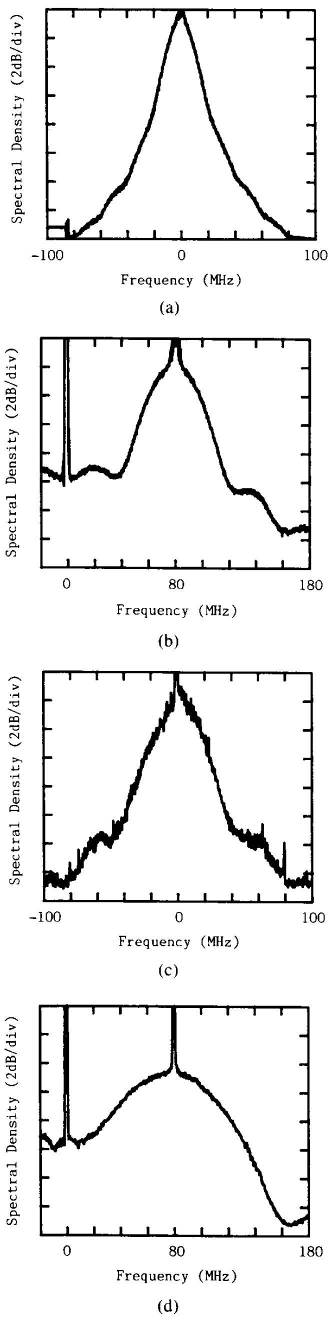

Fig. 4. Spectrum of beat signal measured by RDSH (homodyne) and DSH (heterodyne) method for various fiber lengths. (a) RDSH (homodyne) method for 5 m. (b) DSH (heterodyne) method for 5 m. (c) RDSH (homodyne) method for 2.5 m. (d) DSH (heterodyne) method for 2.5 m.

Fig. 5 shows the relation between the spectral linewidth Δf of an LD under test and the Δf_B (HWHM) of the beat signal. In the figure open and closed circles are HWHM of the beat spectrum measured by the RDSH method and the DSH method, respectively. The solid curves in the figure are calculated from (4) and (5) for $W/2\pi = 13$ MHz. It is found from this figure that measurable range of the RDSH method is wider than that of the DSH method. If we define the resolution as a limit to which the measurement can be carried out within $\pm 5\%$ error, then the resolution of the RDSH and the DSH method are given by

$$\delta f_{RDSH} = 0.39/\tau_o$$
$$\delta f_{DSH} = 0.78/\tau_o. \quad (6)$$

For example, if a fiber of $L = 1$ km and $n = 1.5$ is used, the resolutions of the RDSH and the DSH methods are $\delta f_{RDSH} = 80$ kHz and $\delta f_{DSH} = 160$ kHz, respectively.

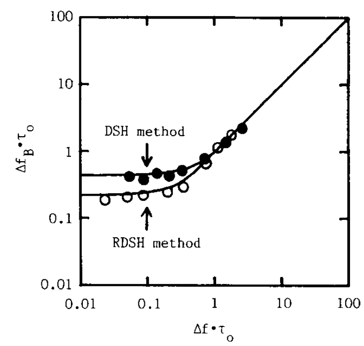

Fig. 5. Relation between spectral linewidth of LD and HWHM of beat signal. Solid lines are calculated curves and open and closed circles are experimental data measured by RDSH (homodyne) and DSH (heterodyne) method, respectively.

III. Effect of Multiple Reflection

If the reflectivities of the fiber ends are increased, multiple reflection can not be omitted. So the effect of multiple reflection is discussed.

Now, let the power reflectivities at the near and far ends of the fiber be R_1 and R_2, respectively. The optical field of the directly emerging beam from the far end is expressed as

$$E_0(t) = E_s \cos [\omega_o t + \phi(t)] \quad (7)$$

where $E_s = \sqrt{PA(1 - R_1)(1 - R_2)}$. After $2k$ times reflections the optical field of the emerging beam is expressed as

$$E_{2k}(t) = z^k E_0(t - k\tau_d) \quad (8)$$

where $z = A\sqrt{R_1 R_2}$. Hence, the detected beat signal $I(t)$ takes the form

$$I(t) = \left\{ \sum_{k=0}^{\infty} z^k E_0(t - k\tau_d) \right\}^2$$
$$= \frac{1}{2} \frac{Es^2}{1 - z^2} \left\{ 1 + 2 \sum_{k=1}^{\infty} z^k \cdot \cos [k\phi_o + \phi(t) - \phi(t - k\tau_d)] \right\} \quad (9)$$

where $\phi_o = \omega_o \tau_d$. The autocorrelation function of $I(t)$ is obtained as

$$R(\tau) = < I(t)I(t+\tau) >$$
$$= B\left\{1 + 2\sum_{k=1}^{\infty} z^k < \cos[k\phi_o + \phi(t) - \phi(t - k\tau_d)] > + 2\sum_{l=1}^{\infty} z^l < \cos[l\phi_o + \phi(t+\tau) - \phi(t + \tau - l\tau_d)] > + 4\sum_{k=1}^{\infty}\sum_{l=1}^{\infty} z^{k+l} < \cos[k\phi_o + \phi(t) - \phi(t-k\tau_d)] \times \cos[l\phi_o + \phi(t+\tau) - \phi(t+\tau-l\tau_d)] >\right\} \quad (10)$$

where $B = |E_s|^4/[4(1 - z^2)^2]$ and $\langle\ \rangle$ denotes time averaging. Thus the power spectrum of the beat signal is calculated by Fourier transforming (10).

If we again assume that $\phi(t)$ is a Gaussian process and a random walk process and that delay time τ_d is much larger than the coherence time of the LD under test, then the power spectrum of the beat signal is expressed as

$$S(\omega) = \frac{P^2 A^4 R_1 R_2 (1 - R_1)^2 (1 - R_2)^2}{(1 - A^2 R_1 R_2)^3} \frac{W}{\omega^2 + W^2}. \quad (11)$$

The beat signal level against the reflectivity of fiber ends in case of $R_1 = R_2 = R$ is calculated from (11) and is shown in Fig. 6 for various values of A. It is clear that the beat signal level depends on the value of the reflectivity of fiber ends R and the fiber transmittance A. The reflectivity R_{opt} optimizing the beat signal level and the corresponding improvement factor relative to the level when $R_1 = R_2 = 4\%$ are tabulated in Table I. Thus the beat signal improvement factor F more than 12 dB is expected. Fig. 7 shows the beat signal level against the far-end reflectivity R_2 when $R_1 = 4\%$. The factor F of about 6 dB is obtained around $R_2 = 34\%$. The values of R_{2opt} and the F are tabulated in Table II.

The experimental result for improvement of the best signal level is shown in Fig. 8. The signal improvements of about 6 and 12 dB relative to the level when $R_1 = R_2 = 4\%$ (curve (i)) are obtained for $R_1 = 4\%$ and $R_2 = 20\%$ (curve (ii)) and $R_1 = R_2 = 20\%$ (curve (iii)), respectively. These values agree with the corresponding calculated values of 5.5 and 11.2 dB.

The difference of the beat signal level between the RDSH and the DSH methods can be evaluated by comparing (11) and (5). For a lossless fiber with cleaved ends ($A = 1$ and $R_1 = R_2 = 4\%$), the beat signal level of the RDSH method is smaller than that of the DSH method by 16.6 dB. This difference is reduced to 2.3 dB by increasing the reflectivity of the fiber ends at an optimum value ($R_1 = R_2 = 50\%$). Thus a comparable beat signal level to that of the DSH method is obtained for a long wavelength region, where a low-loss fiber (typically 0.2 dB/km) is available.

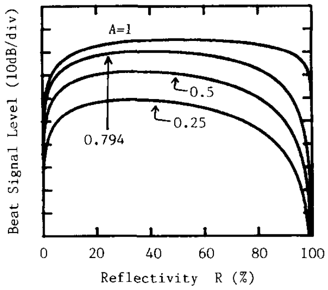

Fig. 6. Calculated beat signal level of RDSH (homodyne) method against fiber ends reflectively ($R_1 = R_2 = R$).

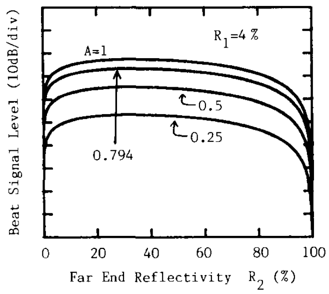

Fig. 7. Calculated beat signal level of RDSH (homodyne) method against far-end reflectivity R_2 when $R_1 = 4\%$.

TABLE I

A	(Loss)	R_{opt}	F
1	(0 dB)	50.0%	14.3 dB
0.794	(1 dB)	40.1%	13.2 dB
0.5	(3 dB)	35.4%	12.5 dB
0.25	(6 dB)	33.8%	12.3 dB

TABLE II

A	(Loss)	R_{2opt}	F
1	(0 dB)	34.2%	6.20 dB
0.794	(1 dB)	33.9%	6.14 dB
0.5	(3 dB)	33.6%	6.08 dB
0.25	(6 dB)	33.4%	6.05 dB

IV. Heterodyning Scheme

For measuring successfully narrowed linewidth of LD's the homodyning scheme is not suitable because of the $1/f$ noise of a photodetector or a marker appearing at 0Hz of RF spectrum analyzer, so the heterodyning scheme is preferable. Fig. 9(a) shows a heterodyning scheme of the RDSH method using bulk-optic components. The optical beam from an LD under test, after passing through an optical isolator (ISO), a half mirror (HM), and a quarter

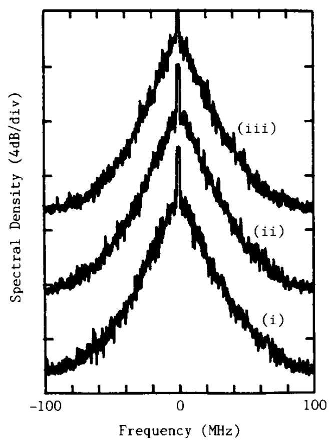

Fig. 8. Experimental result for improvement of beat signal level. (i): $R_1 = R_2 = 4\%$. (ii): $R_1 = 4\%$, $R_2 = 20\%$. (iii): $R_1 = R_2 = 20\%$.

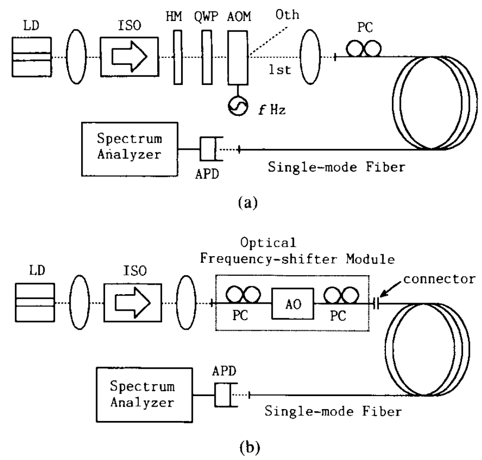

Fig. 9. (a) Example of heterodyning scheme of RDSH method using bulk-optic components. (b) Schematic of RDSH (heterodyne) using optical frequency-shifter module with fiber pigtails. AO: Acoust-optic element.

wavelength plate (QWP), is frequency shifted by f Hz by an acoustooptic modulator (AOM) and is coupled into a single-mode fiber. At the far end of the fiber a part of the optical beam emerges from the fiber (direct beam) and the rest goes back to HM, where a part of the optical beam is reflected again. Then the reflected beam emerges from the far end (delayed beam), and is delayed in time by $\tau = 2L/c$ (L = effective optical length between HM and the far end of the fiber). The direct and delayed beams are frequency shifted by f Hz and $3f$ Hz, respectively. Because of the frequency difference $2f$ Hz existing between the direct and the delayed beams, the beat signal appears around $2f$ Hz at the output of the APD. In order to suppress undesirable homodyne beat signal (attributable to the reflection from the near end of the fiber), a fiber polarization controller is constructed (PC see Fig. 9(a)). This

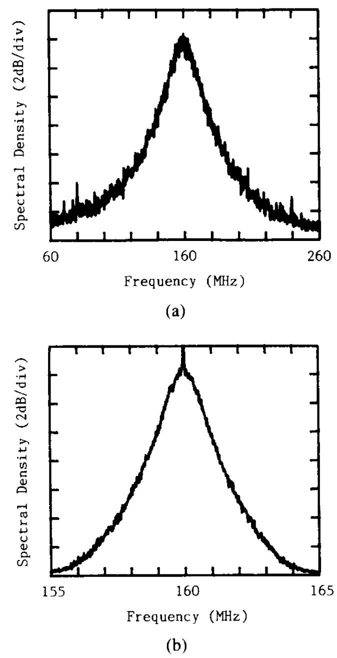

Fig. 10. Spectrum of beat signal measured by RDSH (heterodyne) method. (a) solitary LD (13 MHz HWHM). (b) LD narrowed by optical feedback (760 kHz HWHM).

is used to rotate the polarization of the beam reflected from the near end of the fiber by 90° (orthogonal position). Resultingly homodyne beat signal is easily suppressed by about 12 dB. As far as the beam reflected from the HM is concerned, since the QWP allows additional 90° rotation of the polarization, the heterodyne beat signal can be observed effectively. Fig. 10(a) shows a measured spectrum of the beat signal of an LD (CSP type, 0.83 μm, Hitachi HLP-1400) at $I/I_{th} = 1.79$. The spectrum assumes Lorentzian profile with a 13-MHz HWHM. Fig. 10(b) shows observed spectrum (760-kHz HWHM) of the LD narrowed by optical feedback. These profiles are the same as those measured by the RDSH (homodyne) method. Fig. 11 shows that the measured linewidth of the solitary LD is inversely proportional to the injection current I. The values measured by the RDSH (heterodyne) are in good agreement with those by the RDSH (homodyne).

For a more practical system of the RDSH (heterodyne) method, it is preferable to use a low-loss optical frequency-shifter module with fiber pigtails. The schematic of this arrangement is depicted in Fig. 9(b). The optical beam emitted from the LD under test is coupled into the optical frequency-shifter module, whose output is connected with a long optical fiber. In this case the undesirable homodyne beat signal is generated by a residual reflection from the output fiber end faced to the acoustooptic element. This can be easily suppressed by adjusting fiber polarization controllers constructed on both sides of the acoustooptic element.

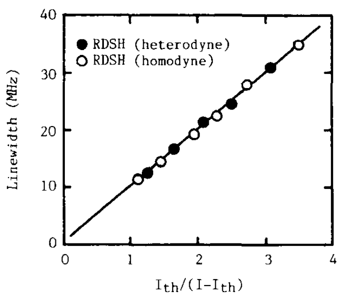

Fig. 11. Dependence of spectral linewidth on laser injection current measured by RDSH (homodyne) and RDSH (heterodyne) method.

V. Conclusion

In this paper we have described the principle and resolution of the RDSH method. Although the principle of the RDSH method is the same as that of the DSH method, the RDSH method requires only a long optical fiber delay line. Two beams producing a beat signal are obtained by utilizing reflections at both ends of the fiber, so the delay time between the two beams is twice that of the DSH method due to a round-trip delay time of the fiber.

It is also pointed that the beat signal level is relatively low due to a large intensity difference between the two beams if cleaved fiber ends (normally 4% in power) are used. This drawback can be improved by increasing the reflectivities of fiber ends by dielectric coating. From the analysis in which the effect of multiple reflection is taken into account it is found that the beat signal level is improved by more than 12 dB when the reflectivities are increased. This is experimentally confirmed when the reflectivities of fiber ends are increased to about 20%.

Finally a heterodyning scheme of the RDSH method using an optical frequency-shifter module with fiber pigtails is described, and its validity is demonstrated by using bulk-optic components.

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Koichi Iiyama was born in Fukui, Japan, on March 19, 1963. He received the B.E. and M.E. degrees in electronic engineering from Kamazawa University, Kanazawa, Japan in 1985 and 1987, respectively.

Since 1988 he has worked as a Research Associate at Kanazawa University. He is currently working in injection locking and noise properties of semiconductor lasers and fiber-optic sensors.

Mr. Iiyama is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Ken-ichi Hayashi (M'88) was born in Kanazawa, Japan in 1943. He received the B.E. degree in electronic engineering from Kanazawa University, Kanazawa, Japan, in 1966 and the D.E. degree from Nagoya University, Nagoya, Japan in 1977.

Since 1966 he has been with the Department of Electronic Engineering, Kamazawa University and is now a Professor in the Department of Electrical and Computer Engineering, Kanazawa University. He is now working in research on injection locking, modulation, and noise properties of semiconductor lasers and fiber-optic sensors.

Dr. Hayashi is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Yoshio Ida received the B.E. and D.E. degrees in electrical engineering from Nagoya University, Nagoya, Japan in 1951 and 1967, respectively.

Since 1969 he has been a Professor at Kanazawa University, Kanazawa, Japan, and is now a Professor in the Department of Electrical and Computer Engineering, Kanazawa University. He is currently working in research on injection locking, modulation, and noise properties of semiconductor lasers and fiber-optic sensors.

Dr. Ida is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Hitoshi Ikeda was born in Osaka, Japan on March 28, 1967. He received the B.E. degree in electrical and computer engineering from Kanazawa University, Kanazawa, Japan in 1989. He is now working toward the M.E. degree at Kanazawa University.

Mr. Ikeda is a member of the Institute of Electronics, Information and Communication Engineers of Japan.

Yoshihisa Sakai was born in Kanazawa, Japan on October 3, 1963. He received the B.E. and M.E. degree in electronic engineering from Kanazawa University, Kanazawa, Japan in 1986 and 1988, respectively.

Since 1988 he has been with NTT Opto-electronics laboratories, Atsugishi, Japan, where he has worked on frequency stabilization of semiconductor laser using molecular absorption lines of C_2H_2.

Mr. Sakai is a member of the Institute of Electronics, Information and Communication Engineers of Japan and the Japan Society of Applied Physics.