Microwave Generation Using Laser Heterodyne Technique with Independent Controllability in Frequency and Phase

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Abstract—**This paper describes the theoretical and experimental investigation of a scheme for microwave generation using laser heterodyne. The frequency of the generated microwave is controlled by changing the frequency difference between two temperature-controlled semiconductor laser diodes. The phase difference between the two microwaves is controlled by changing the difference between the two states of polarization of two laser beams. An attractive feature of this scheme is its easy and independent controllability in frequency and phase.**

I. Introduction

RECENTLY, there has been a rapid development in the applications of optoelectronics to microwave techniques [1]–[8]. As one of these applications, a laser heterodyne technique for the generation of microwave or millimeter wave [6]–[8] is quite attractive, given the existence of semiconductor laser diodes with narrow linewidths and high-speed photo detectors. In this paper we propose a new laser heterodyne technique for microwave generation in which two laser beams with the different states of polarization (SOP) are mixed and converted to two microwave signals each with an orthogonal linear polarization. Since the phase difference between the two microwave signals reflects the SOP of light [9], phase difference between these signals can be controlled by the SOP difference between the two laser beams. Since SOP's are almost independent of the small amount of frequency change of laser diodes, which determines the microwave frequency, the phase difference is also independent of the microwave frequency. It means, in this scheme, that microwave frequency and phase can be independently controlled. Although this feature is available in [4], [7], and [8], the control of both quantities is much easier in the proposed scheme.

II. Operation Principle

Fig. 1 shows the experimental setup of the proposed microwave generation scheme. Two laser beams with different SOP's from two laser diodes, LD_1 and LD_2, are launched onto a beam splitter (BS) and superposed together. The superposed beam is again splitted into two beams whose 45° tilted polarization components are selected by analyzers and detected by photodetectors (PD's). Due to the nonlinearity of the detectors, two microwave signals having the same frequencies corresponding to the frequency difference between the two laser beams are obtained.

Angular lasing frequencies of LD_1 and LD_2 are denoted by ω_1 and ω_2, respectively. Although the beam from LD_1 is linearly polarized in the experiment, here we treat the general case in which both beams are elliptically polarized and their principal axes coincide with the horizontal axis as shown in Fig. 2. In this case, complex amplitudes of transverse electric field components of these beams coming from the $LD_i\,(i = 1,\, 2)$ are described as follows:

$$\begin{cases} E_{ix'} = A_i \cos\psi_i e^{j(\omega_i t - \beta_i z + \phi_i)} & \text{(1a)} \\ & (i = 1,\, 2) \\ E_{iy'} = jA_i \sin\psi_i e^{j(\omega_i t - \beta_i z + \phi_i)} & \text{(1b)} \end{cases}$$

where A_i denotes the amplitudes of the elliptically polarized beams, ψ_i is related to the ellipticities of these beams. $\beta_i = \omega_i\sqrt{\varepsilon_0\,\mu_0}$ $(i = 1,\, 2)$ are the propagation constants of the beams in which ε_0 and μ_0 are the permittivity and the permeability of air, respectively. In (1), ϕ_i is the initial optical phase of the beam from LD_i at the beam splitter. As shown in Fig. 2, x'-axis and y'-axis are taken parallel and perpendicular to the horizontal axis, respectively. These beams are combined and equally splitted into two beams by means of the beam splitter. It should be noted that one of the incident beams gets π radian phase shift at the reflection surface of the beam splitter. To avoid complexity this phase shift is omitted in this analysis and considered later. Fig. 2 also shows the relation between the SOP's of the two laser beams and the orientation of the analyzers in front of the two photo detectors. Axes of the two analyzers are mutually orthogonal and tilted 45° with respect to the principal axes of the elliptical polarizations of the laser beams. Thus, orthogonal components of the superposed beam are selected by analyzers whose axes coincide with the x- and y-axes in Fig. 2. Using (1), x- and y-components of the electric fields which originate from the $LD_i\,(i = 1,\, 2)$ are written as

$$\begin{cases} E_{ix} = \dfrac{1}{\sqrt{2}}(E_{ix'} - E_{iy'}) & \\ \quad = \dfrac{A_i}{\sqrt{2}} e^{j(\omega_i t - \beta_i z + \phi_i - \psi_i)} & \text{(2a)} \\ & (i = 1,\, 2) \\ E_{iy} = \dfrac{1}{\sqrt{2}}(E_{ix'} + E_{iy'}) & \\ \quad = \dfrac{A_i}{\sqrt{2}} e^{j(\omega_i t - \beta_i z + \phi_i + \psi_i)}\,. & \text{(2b)} \end{cases}$$

Manuscript received January 2, 1995; revised March 19, 1995.

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IEEE Log Number 9413701.

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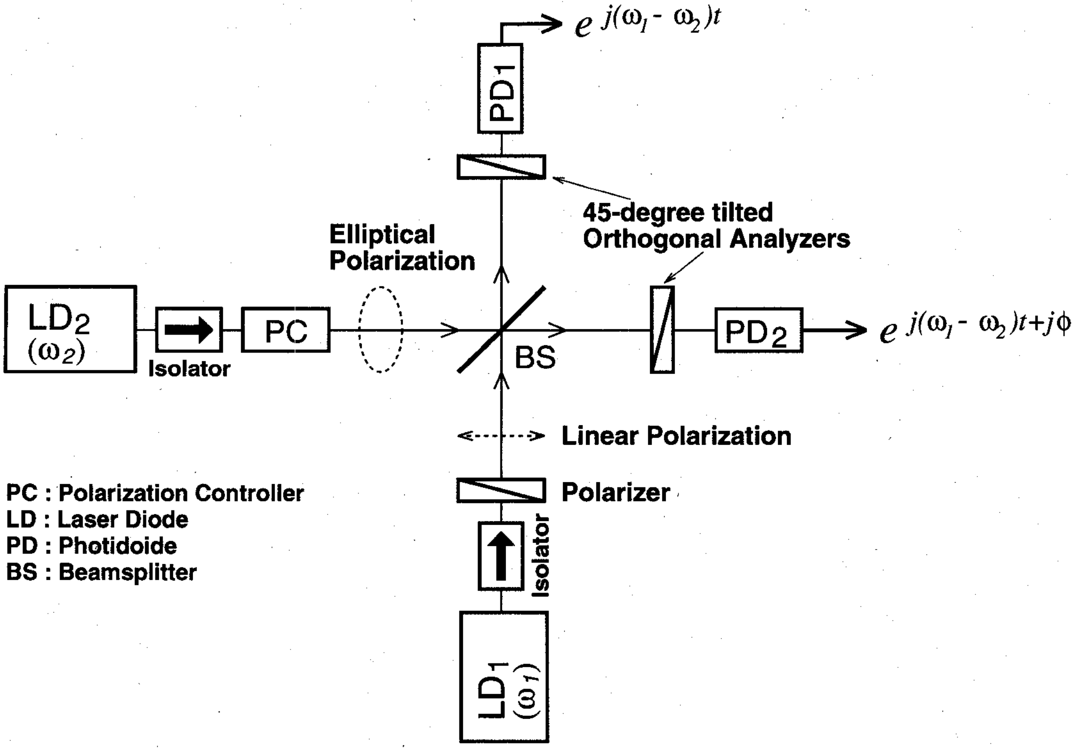

Fig. 1. Proposed microwave generation scheme using a laser heterodyne technique.

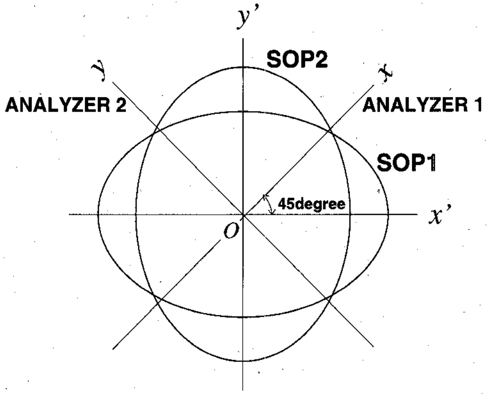

Fig. 2. Two elliptical polarizations with different frequencies and two orientations of the two analyzers in front of the two photo detectors.

As both x- and y-components have optical signals of the angular frequency ω_1 (from LD_1) and ω_2 (from LD_2) they are mixed at the two photo detectors. The complex amplitudes of the photo currents I_i of PD_i $(i = 1, 2)$ are thus described as follows:

$$\begin{aligned} I_1 &= CE_{1x} \cdot E_{2x}^* \\ &= \frac{CA_1A_2}{2} e^{j\{(\omega_1-\omega_2)t-(\beta_1-\beta_2)z_1+(\phi_1-\phi_2)-(\psi_1-\psi_2)\}} \end{aligned} \tag{3a}$$

$$\begin{aligned} I_2 &= CE_{1y} \cdot E_{2y}^* \\ &= \frac{CA_1A_2}{2} e^{j\{(\omega_1-\omega_2)t-(\beta_1-\beta_2)z_2+(\phi_1-\phi_2)+(\psi_1-\psi_2)\}} \end{aligned} \tag{3b}$$

where z_i is the distance between the beam splitter and the photodetector PD_i $(i = 1, 2)$. C is a constant related to the detector responsivity or quantum efficiency. It should be noted that the two photo detectors are assumed to have identical characteristics.

It follows that the angular frequency of generated microwave is $|\omega_1 - \omega_2|$. The phase difference between the two microwaves, θ, is

$$\begin{aligned} \theta &= \tan^{-1} \frac{I_2}{I_1} \\ &= 2(\psi_1 - \psi_2) + \sqrt{\varepsilon_0 \mu_0}(\omega_1 - \omega_2)(z_1 - z_2). \end{aligned} \tag{4}$$

The first term of this phase difference is purely originated from the polarization-state difference of the incident laser beams, whereas the second term is originated from the path difference $(z_1 - z_2)$ and the frequency difference between the laser beams. If the path difference coincides with zero, phase difference depends on the SOP difference only. It means that as long as the frequency change does not alter the SOP, the generated microwave frequency and the phase difference between the two microwave signals can be controlled independently. If the pass difference is not zero, the second term should be considered as the phase error. From (4) it is found that this phase error can be kept small enough if the condition below is satisfied

$$\frac{|z_1 - z_2|}{\lambda_m} \ll 1 \tag{5}$$

where λ_m is the microwave wavelength. This condition can be easily satisfied by simply equalizing the length z_1 and z_2. As for the scheme in [7] and [8], path difference adjustment to realize the independent controllability is not as simple as this scheme. In the following experiment, the laser beam from

LD_1 is linearly (horizontally) polarized whereas the beam from LD_2 is elliptically polarized. In this case the phase difference can be controlled from zero to 2π by changing ψ_2, the ellipticity of the beam from LD_2 in the range from zero to π. As previously noted, there exists the phase bias of π radian because one of the incident beams gets the phase shift at the surface of the beam splitter. Thus actual phase difference θ in this case is in the range from $-\pi$ to π.

III. EXPERIMENTAL RESULTS

In the experimental setup shown in Fig. 1, two temperature-controlled InGaAs/InP DFB lasers operating at 1.3 μm are used. The output powers of the LDs were 3.0 and 4.0 mW, respectively, when the injection currents were 35 mA. The spectral linewidths (FWHM's) of these LD's were estimated using delayed self-heterodyne technique [10] and found to be 15.9 and 19.0 MHz, respectively. The beam from LD_1 is linearly polarized along the x'-axis (parallel to the paper) whereas the beam from LD_2 is controlled by the polarization controller, which consists of a $\lambda/4$ and a $\lambda/2$ plate, and is converted to an elliptical polarization whose principal axis coincides with x'-axis. This polarization controller could be replaced by an electrooptic controller for high-speed applications. Two Ge avalanche photodiodes are used to generate microwave signals. The avalanche gain M was set to 1 in order to keep the excess noise as low as possible and to keep the cutoff frequency as high as possible. The cutoff frequency of these photodetectors is 3 GHz. The microwave frequency is controlled by changing the ambient temperature of LD_1. The temperature coefficient of the laser diodes is about 15 GHz/°C. It should be noted that by using laser diodes with narrower linewidths and photodetectors with higher cutoff frequencies, generated microwave bandwidth will be broader.

In this scheme, as mentioned above, two beams are equally splitted by the beam splitter and, furthermore, half of these components are selected by the analyzers. Then, the powers of the two laser beams in front of the detectors become $P_1/4$ and $P_2/4$, respectively, where P_1 and P_2 denote the output powers of the two LD's. The magnitude of the photo currents I_p thus becomes

$$\begin{aligned} I_p &= 2\sqrt{\frac{P_1}{4}\frac{P_2}{4}}\mathcal{R} \\ &= \frac{1}{2}\sqrt{P_1 P_2}\mathcal{R} \end{aligned} \tag{6}$$

where $\mathcal{R}$ is the detector responsivity and is 0.8. Assuming the above values of output power ($P_1 = 3.0$ mW and $P_2 = 4.0$ mW) the estimated microwave power P_m for the 50 Ω load R_L is

$$\begin{aligned} P_m &= \tfrac{1}{2}R_L I_p^2 \\ &= \tfrac{1}{8}R_L P_1 P_2 \mathcal{R}^2 \\ &= 4.8 \times 10^{-2}\,\text{mW} \quad (= -13.2\,\text{dBm}). \end{aligned}$$

On the other hand, the measured microwave power was -20 dBm. The authors believe that the discrepancy between these values is mainly due to the imperfect spatial overlap of two laser beams at the detectors.

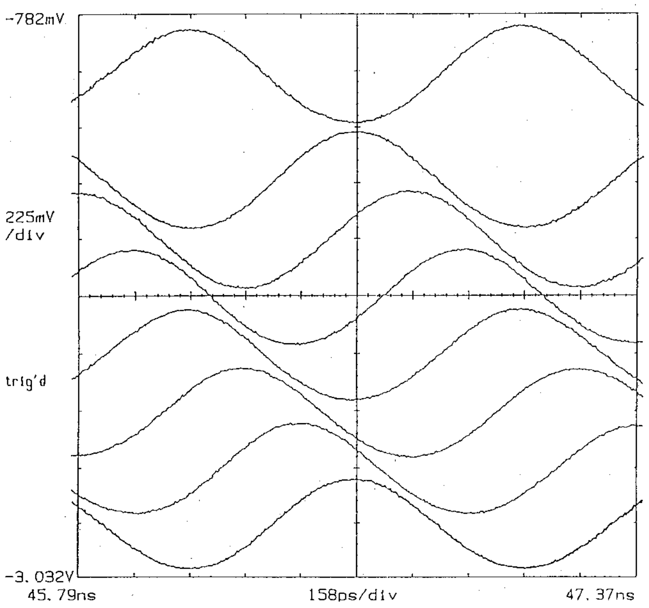

Fig. 3. Microwave phase controlled by the SOP of the beam from LD_2.

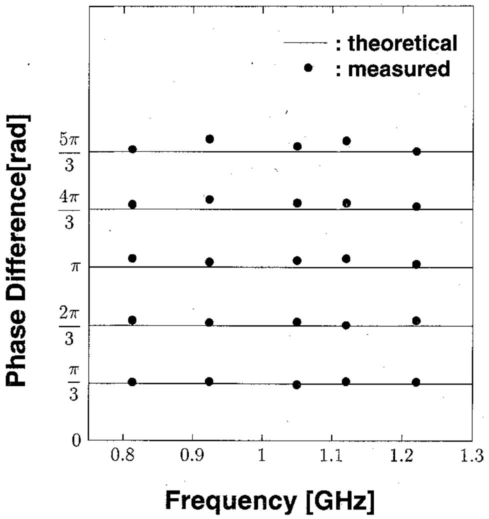

Fig. 4. Frequency dependence of the phase in the case of $z_1 - z_2 = 0$.

The measured spectral linewidth (FWHM) of the microwave is 40 MHz, which is approximately the sum of the laser linewidths. Fig. 3 shows the phase controlled by the polarization of the beam from LD_2. The trace on the top shows a signal produced by PD_1. The rest of the seven traces show signals produced by PD_2 with the SOP changed. The second trace corresponds to the case of $\psi_2 = 0(\theta = \pi)$. A lower trace has a larger value of ψ_2 than the above trace by $\pi/6$. The lowest (8-th) trace thus corresponds to the case of $\psi_2 = \pi(\theta = -\pi)$. It shows that the phase can be controlled only by changing the polarization ellipticity of the beam from LD_2.

Fig. 4 shows the frequency dependence of the phase under the condition $z_1 - z_2 = 0$. Solid lines are the controlled (theoretical) values of the phase whereas dots are measured values. A good agreement is seen between these experimental and theoretical values. It is found that the phase difference can almost be independent of the frequency change as long as the path difference is zero.

These results verify the principle of the proposed scheme in which the frequency and phase of generated microwave are controlled by the temperature of one of the lasers and the SOP difference of the two beams, respectively. It was also found that the frequency and the phase can be controlled independently as long as there is no path difference.

IV. CONCLUSION

A new laser heterodyne scheme for microwave generation was proposed and experimentally demonstrated. The attractive feature of this scheme is that the independent controllability of frequency and phase was verified under the small path difference condition, which can be easily realized. Moreover, the frequency and the phase can be controlled very easily by changing the lasing frequency and the SOP, respectively.

ACKNOWLEDGMENT

The authors would like to thank H. Iida (currently with Sony Co., Ltd.) and T. Komatsuzaki (currently with Matsushita Communication Industry Co., Ltd.) for their technical assistance. The authors also wish to thank Prof. K. Atsuki for his helpful comments.

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Eikichi Yamashita (M'66–SM'79–F'84), for a photograph and biography, see p. 337 of the February 1995 issue of this TRANSACTIONS.