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Directional Stability of the Optical Heterodyne Detector with Integrated Diffraction Grating

回折格子をもちいた一体化光ヘテロダイン検出器の機械的方向変化に対する安定性について

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This letter describes the principle and the directional stability of the new optical heterodyne detector which has a grating coupler integrated on a Silicon photodiode.[1] Unlike the conventional detectors, the wavefront matching of the signal (S) and the local (L) waves is achieved by an integrated diffraction grating, which is directly fabricated on top of the photodiode surface as shown in Fig. 1.

Suppose the signal and the local plane waves are obliquely incident to the shallow grating and partly diffracted as shown in Fig. 1. The wavefront matching condition of the two waves, which is necessary in the heterodyne detection, can be derived from the surface momentum conservation law as shown in Fig. 2. The wavefront matching can be simply expressed as

$$k(\sin\theta_s+\sin\theta_l)=K \qquad (1)$$

where θ_s and θ_l are the incidence angle of the signal and the local waves, respectively, k is the wavenumber of both waves (note that their optical frequencies are approximately equal), and $K=2\pi/\Lambda$ where Λ is the period of the grating.

To demonstrate the effectiveness of this new heterodyne detection scheme experimentally, a photoresist grating is first formed on the SiO_2 coating (~0.2 mm in the thichness) of commercial silicon photodiode, by a holographic exposure using a He-Cd laser ($\lambda=442$ nm). The grating period is 514 nm. The detector thus fabricated is then placed in the heterodyne detection system schematically shown in Fig. 3. The incident

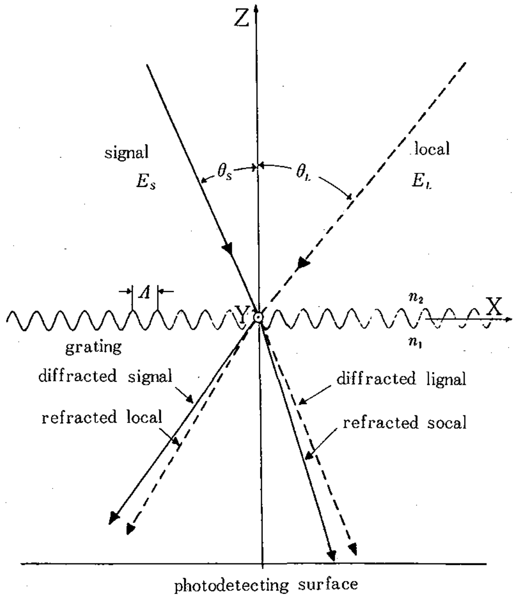

Fig. 1 Propagation directions of signal and local waves in vicinity of integrated diffraction grating forced on top of photodiode surface.

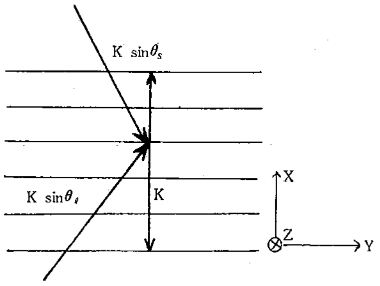

Fig. 2 The surface momentum conservation law on the grating.

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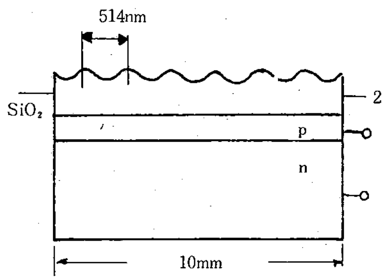

Fig. 3　The configuration of the heterodyne detector integrated with grating.

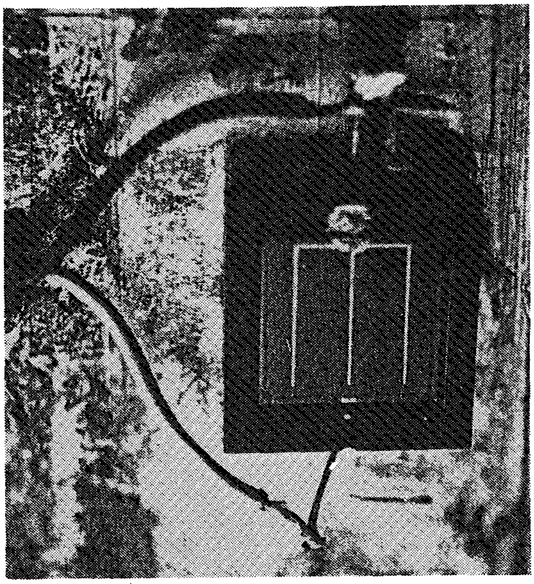

Fig. 4　Photograph of the experimental heterodyne detector.

signal and local waves are quasiplane waves of He-Ne laser (0.63 μm) of spotsize 0.5 mm. The size of the photodiode with grating is 7×10 mm. The photograph of this device is shown in Fig. 4.

Next, we consider the effect of the wavefront mismatch due to the optical misaligment, which is a serious problem in conventional optical heterodyne dection systems. Suppose that the defference between the tangentical components of the signal and the local wave vectors on the detector surface is k. The heterodyne output for the misaligned incidence is known to be proportional to a coefficient F: for the plane wave incident on a rectangular detector with size L_x and L_y,

$$F=\left|\operatorname{sinc}\frac{\varDelta k_x L_x}{2}\right|^2\left|\operatorname{sinc}\frac{\varDelta k_y L_y}{2}\right|^2 \qquad (2)$$

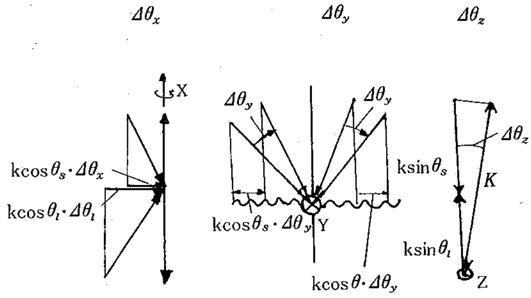

Fig. 5　The trangential wave-vectors for the rotations of the detector.

and, for the Gaussian beams much narrower than detector size,

$$F=\exp\left\{-\frac{1}{2}\left(\frac{1}{w_{sx}^2}+\frac{1}{w_{lx}^2}\right)(\varDelta k_x)^2\right\}\times\exp\left\{-\frac{1}{2}\left(\frac{1}{w_{sy}^2}+\frac{1}{w_{ly}^2}\right)(\varDelta k_y)^2\right\} \qquad (3)$$

where w_{sx} denotes the spotsize of the signal wave measured along the x-axis on the detector surface. Subscript 1 is for the local wave. Eqns. 3 and 4 show the stringent requirements of wavefront matching, which are imposed not only on the conventional heterodyne detector but also on the new detector. The present integrated detector, however, has the advantage over the conventional detector structure (consisting of a half-mirror and a diode) because the use of an integrated grating firmly fixed to the diode is very effective in reducing the wavevector mismatch for an angular and a translational mechanical misaligment of the detector. To show this point, we assume first that the exact aligment of the signal and the local waves is achieved and then the mechanical misaligment of the present detecter is brought forth by the axial rotation ($\varDelta\theta_x, \varDelta\theta_y, \varDelta\theta_z$) of the device around the (x, y, z) axis. The wave-front mismatch $\varDelta k$ in this case can be calculated by using the vector momentum conservation law on the grating surface as

$$\varDelta k_x=-k(\cos\theta_s-\cos\theta_l)\varDelta\theta_y \qquad (4)$$

$$\varDelta k_y=-k(\cos\theta_s-\cos\theta_l)\varDelta\theta_x-K\varDelta\theta_z \qquad (5)$$

In those equations, both grating and detector surfaces are assumed to be parallel. The surface momentum conservation law is shown in Fig. 5. Eqns. 5 and 6 show that the mismatch due to the rotation around the x and y axes can be completely removed by

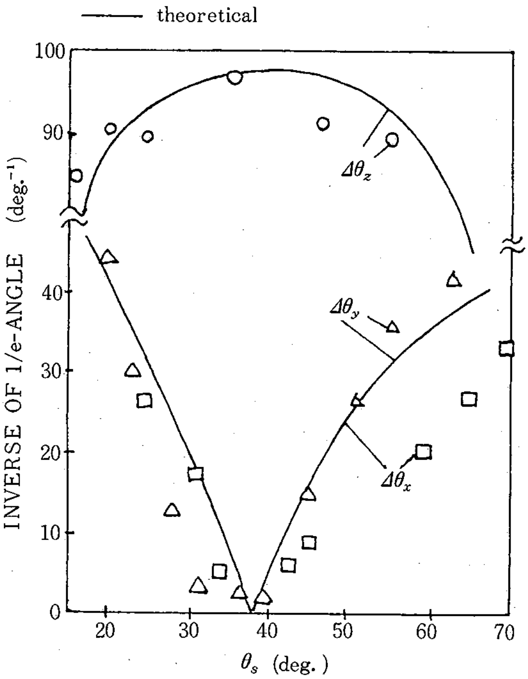

Fig. 6 The directional stability as a function of θ_s.

setting $\theta_s = \theta_l$. On the other hand, the mismatch due to the translational misaligments is negligible. To prove such an expectation, the tolerable angular misaligment is mesured and its inverse is plotted against the incident angle of the signal wave, θ_s in Fig. 6. The data agrees very well with the theoretical values when the Gaussian beams are incident, calculated from Eqns. 4-6, proving that the optical aligment of the present detector is much easier than that of the conventional one.

The typical diameter of the photodiodes and the APD is about 200 μm. Even when a 200 μm Gaussian beam is incident, it can be well approximated by a plane wave; hence this principle can be applied to such photodiodes. When the diameter of the photodiode is so small as to be comparable to the period of the grating, the diffraction grating can exist no more and this principle becomes inapplicable.

This principle can be extended to any gratings with zeroth and the first order diffraction. For example, it may be convenient to utilize a zone plate. By this zone plate, which is a special case of the grating, the local wave converted to the matched wavefront by the first order diffraction, with the signal with the zeroth order diffraction.

In this case, the stability of the heterodyne detection can not be improved, because the image point of the local wave will move from the signal point source by the mechanical movement of the device (the zone plate+detector). The decrease of the heterodyne output by two different point sources was analyzed by one of the authors.[2]

In conclusion, a new optical heterodyne detector having an integrated diffraction grating is proposed an demonstrated. The new detector with its compactness and easy alignability is expected to play an important role in heterodyne optical communication as well as in various mesuring systems utilising optical heterodyne detection.

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