LONG-LIFE MICRO-LASER ENCODER

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ABSTRACT

We have developed a micro-laser encoder that can detect displacements relative to an external grating scale with resolution on the order of 10 nm. Its size is only a few percent of a conventional encoder's size. A long-lasting InP laser diode with a wavelength of 1550 nm is bonded, along with several photodiode chips, within an alignment accuracy of ±1 μm onto a silicon planar lightwave circuit chip. The chip is 2.3 mm x 1.7 mm and includes a fluorinated polyimide light waveguide fabricated in advance. A wide gap of more than 600 μm was obtained between the external grating scale and the encoder despite the tiny size of the sensor. When used as a rotary encoder, the number of rotations could also be detected. Thus, this microencoder satisfies the market requirements for practical use.

INTRODUCTION

Encoders are widely used as the positioning sensors that measure revolution angle or displacement when incorporated into rotating motors, stages, manipulators, actuators, and so on. We have been developing an integrated microencoder, aiming at reducing the size while raising the accuracy, and have reported a microencoder monolithically integrated on a GaAs substrate [1], [2], [3]. That encoder was less than 1 mm in size, and a few thousand encoder chips could be simultaneously fabricated from a two-inch-diameter crystalline laser substrate. The gap between the encoder and the external scale was approximately 200 μm, and good signals were obtained. However, a longer life, rotation number (Z signal) acquisition, and a wider gap between the external scale and the encoder was required for practical use. To satisfy

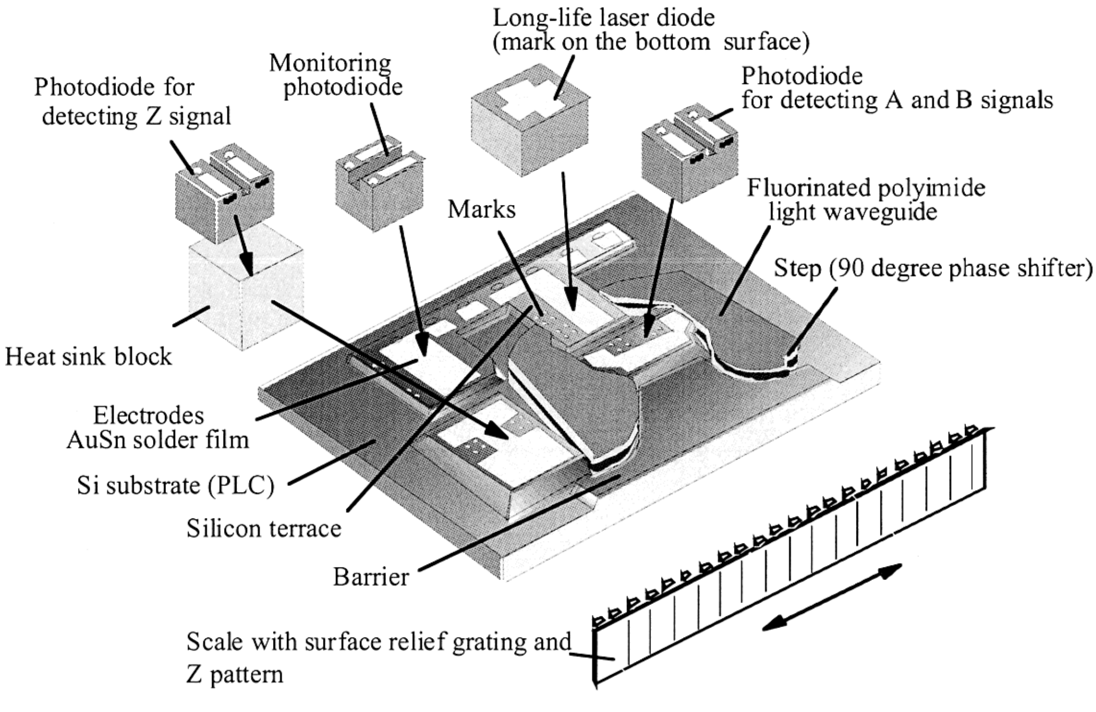


Fig. 1 Schematic of the developed encoder which is formed by bonding a long-life laser diode. In this illustration, the scale is linear and the Z pattern is omitted.

these requirements, we have developed an hybrid encoder formed by accurately bonding a laser diode (LD) with a long life (nominal life span: 100,000 hours) and photodiode (PD) chips onto a silicon planar lightwave circuit (PLC). A fluorinated polyimide waveguide and a silicon terrace for mounting the LD were formed in the PLC.

The measurement principle is basically the same as for our previous monolithically integrated encoder[3]. The two beams emerging from the individual waveguides interfere on the photodiode with the two-segment area receiving the light after it has been reflected at the grating scale. When the scale was moved relative to the encoder by the pitch of the grating scale, a two-period sinusoidal signal could be obtained. By dividing the signal by the phase, we could obtain resolution on the order of 10 nm. Unlike in our monolithically integrated encoder, though, the returning light affected the encoder signal characteristics (returning light: light returning to one waveguide after the light beam emerging from the other waveguide was reflected at the scale).

Although the hybrid encoder is more difficult to fabricate than the monolithically integrated encoder (for example, the bonding must be highly accurate), it can use the silicon PLC as a heat sink for diffusing heat generated by the oscillating laser diode, can be integrated with electronic integrated circuits (ICs), and can choose most preferable optical components. These advantages are the main reasons for developing the hybrid encoder.

STRUCTURE AND DESIGN

We produced the hybrid encoder chips by bonding optical elements, such as the LDs, PDs, and heat-sink blocks on silicon substrate with terraces and a barrier. On the silicon substrate, prior to the electrode, the solder film and fluorinated polyimide waveguide were formed as schematically shown in Fig. 1. The silicon terraces and barrier were fabricated by anisotropic etching in KOH solutions. Figure 2 shows an SEM photograph of the hybrid encoder chip mounted on a header. A Fabry-Perot InGaAsP/InP laser diode with a wavelength of 1550 nm, a threshold current of less than 15 mA, and a FWHM (full width at the half maximum intensity) of 29 degrees in the perpendicular direction and 26 degrees in the horizontal direction was mounted with the active layers down (junction down). Two-segment photodiodes (bias voltage of -5 V, responsivity of 0.91 A/W, and dark current of 0.03 - 0.28 nA) were mounted with the active layers up (junction up). The photodiodes were used to detect A and B signals corresponding to displacements or revolution relative to the scale, to monitor the laser power, and to detect the Z signal. The PLC was fabricated by forming a fluorinated polyimide light waveguide, electrodes, and a AuSn solder film on a silicon substrate. The PLC also conducted heat away from the active layer of the laser diode. The Si terrace and heat sink blocks were also used to adjust the height of the active layer of , respectively, the laser diodes and photodiodes.

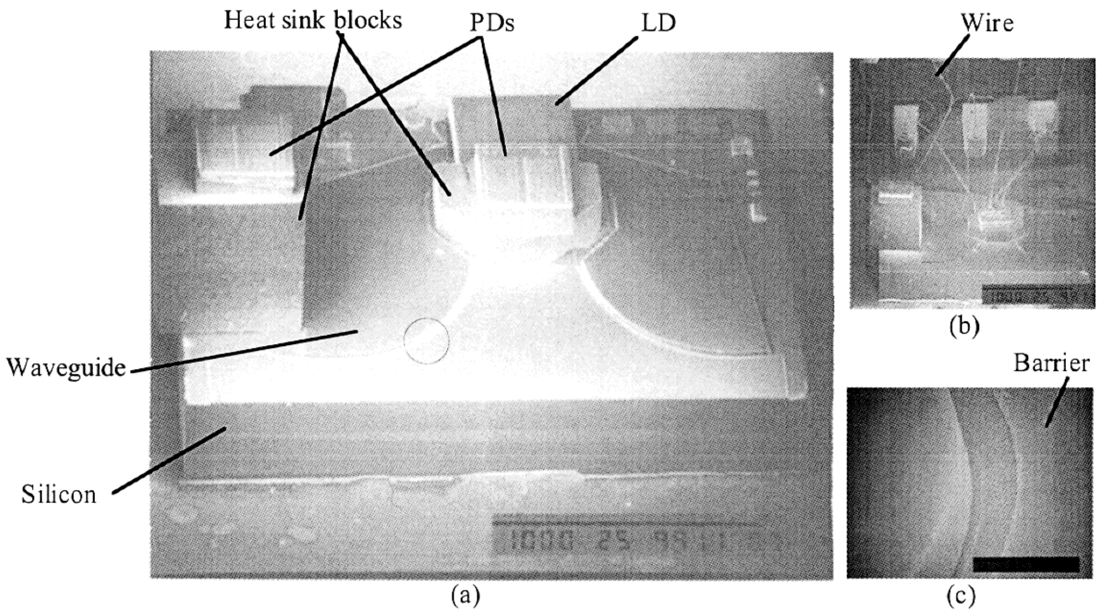


Fig. 2 SEM photographs of hybrid encoder chip mounted on heade: (a) before and (b) after wire bonding. (c) An enlarged view from circled region shown in (a).

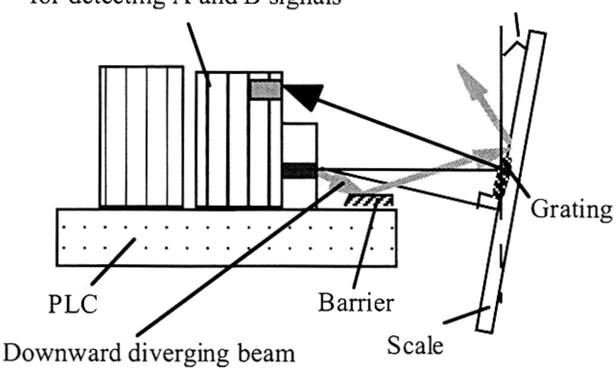


Fig. 3 Returning light prevented by tilting the encoder chip, which has a barrier in front of the waveguide, relative to the scale.

At the end of one waveguide, a step was formed whpse height corresponded to a quarter of a wavelength; this produced a 90-degree phase shift. The divergence of the beam emerging from the polyimide waveguide, whose core thickness was 5 μm, was 0.8 degrees in the horizontal direction and 7 degrees in the perpendicular direction in FWHM: one-thirtieth and one-quarter, respectively, of that of the LD alone.

The LD in our hybrid encoder was affected by returning light [5]because of the greatly improved coupling efficiency. The intensity of the returning light varied because of the changing gap between the scale and the encoder, and this created encoder signal noise. To eliminate the returning light, the header where the encoder chip was placed, was simply tilted by a few degrees. As a result, the central beam does not enter the waveguide. However, part of the downwardly diverging beam could still enter the waveguide as a returning beam after being reflected by an external grating scale. Thus, we formed a silicon barrier, to prevent the downward divergence, close to the core layer in front of the waveguide. The downwardly diverging beam was reflected upward by the barrier as shown in Fig. 3.

The Z signal was detected through the beam that diverged upwardly from the waveguide after being reflected by a highly reflective metal pattern (the Z pattern) at the upper part of the grating in the scale. When the beam in the center of the intensity profile reaches the active layer of the central photodiode, the beam diverged in the perpendicular direction, or the beam in the perimeter of the intensity profile reaches the active layer of Z signal detection photodiode, which is placed on a few hundred-micrometers-thick heat sink to adjust the height of the active layer. A 300-μm-wide grating pattern with a pitch of 3.2 μm was used to detect A and B signals, and a Z pattern that was 10 μm wide in the radial direction, were formed in the scale on the silicon disk (Fig. 4).

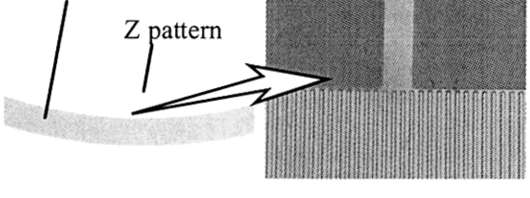


Fig. 4 (a) Grating used to detect A and B signals and the pattern for detecting the Z signal in the scale. (b) An enlarged view.

ACCURATE BONDING

The LD and PDs were aligned and bonded to the PLC by using marks formed on the surfaces close to the active layers of the PDs and LD and on the surface of the PLC. However, the marks could not be seen in visible light

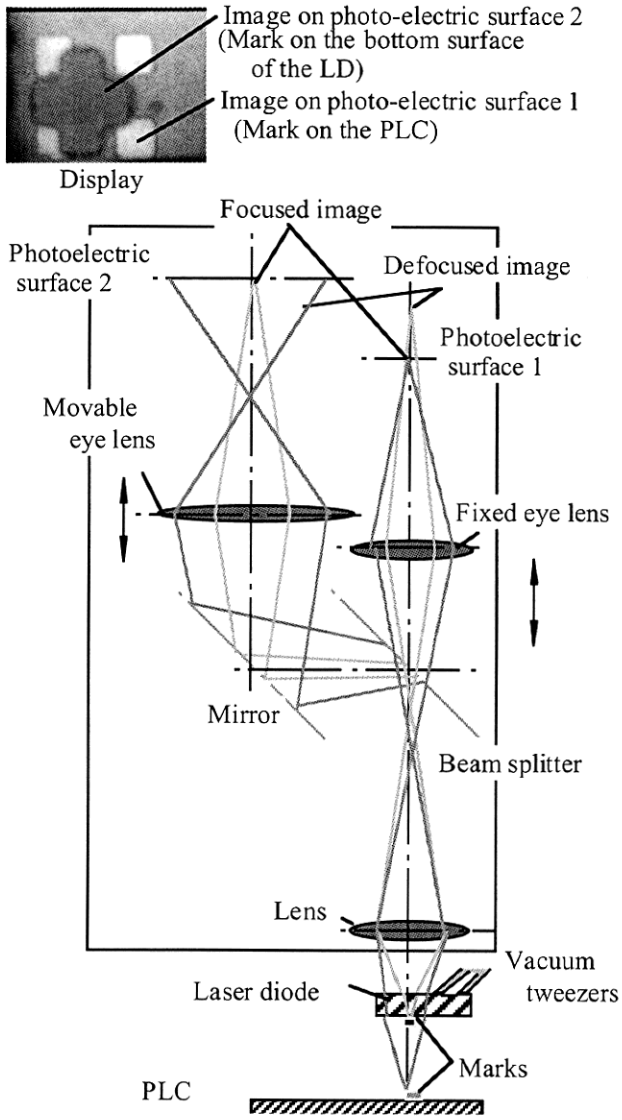
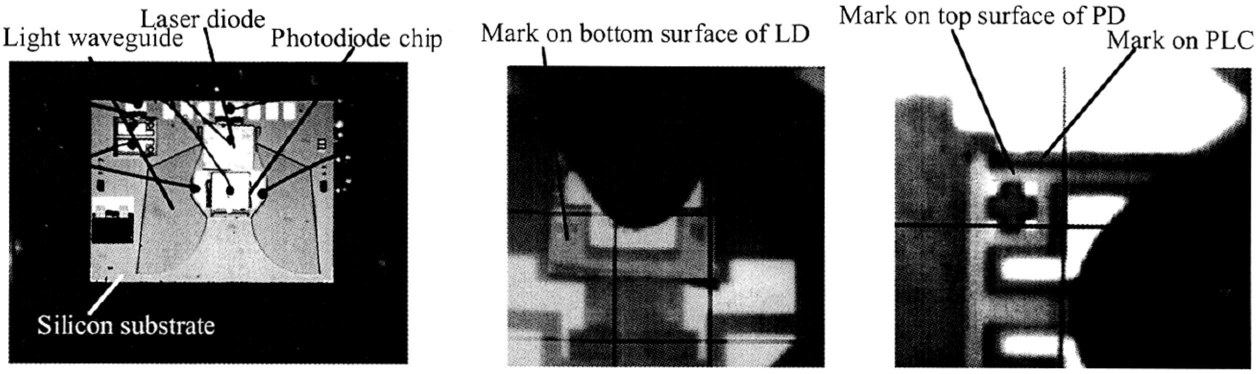


Fig. 5 Accurate bonding based on automatic and simultaneous infrared focusing on individual marks.



(a) (b) (c)

Fig.6 (a) Integrated microencoder after bonding of the laser diode and photodiodes onto a silicon substrate. (b) The laser diode bonded with its active layer down, and (c) the photodiodes bonded with their active layers up.

during alignment, because the LD and PLC marks were blocked by the LD chips. Thus, we used an infrared light beam transmitted from the LD or PD in the alignment. Even so, we could not focus simultaneously on the marks of the LD or PD and the PLC, because of the large gap between the marks. We therefore developed an auto-focusing mechanism that simultaneously focused on the respective alignment marks [4] as shown in Fig. 5. Alignment in the thickness direction was not necessary because we used optical elements whose heights were controlled to make the optical device active layer height coincide with the core height of the light waveguide. Since the crystalline layer thickness of the LD chip is more accurate than the chip thickness, the alignment was done with the junction down. The heights could be accurately adjusted by controlling the total combined thickness of 1) the crystalline layer and the electrode film in the laser diode, the AuSn solder film, the electrode film, and the Si terrace height, and 2) the total combined thickness of half the core and the lower cladding layer in the waveguide. Precise alignment, especially for a laser diode, could be done immediately after the AuSn solder had been melted by heating the PLC. The good-quality images obtained through auto-focusing led to good contour lines being obtained for the marks, less time needed tofocus on them, and faster imaging.

Microphotographs taken by this bonding equipment are shown in Fig. 6(a) for a microencoder after the laser diode and photodiodes were bonded onto a silicon substrate. The LD was bonded with its active layers down (Fig. 6(b)), and the photodiodes were bonded with their active layers up (Fig. 6(c)). This bonding method can be used to bond optical chips in either a junction-down or junction-up orientation.

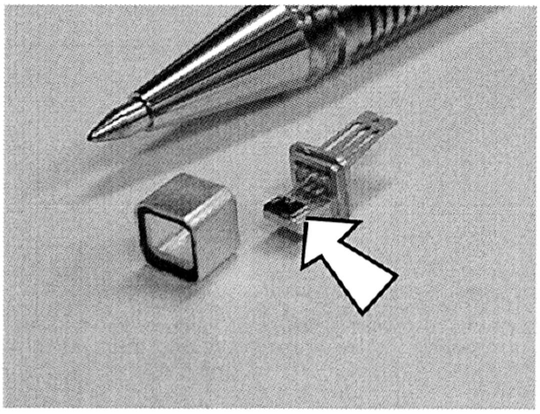


Fig. 7 Photograph of the microencoder before packaging

ENCODER CHARACTERISTICS

Figure 7 shows a photograph of the micro encoder before it packaged with a cover. The light beam emerges from a transparent glass window at the front of the cover. We evaluated the encoder characteristics using the packaged encoder. When the scale was moved relative to the encoder by the pitch of the grating scale, a two-period sinusoidal signal could be obtained. The gap between the encoder and the scale was approximately 600 μm without the package and 500 μm with the package. Figure 8(a) shows sinusoidal intensities I_A and I_B from the two photodiodes when the packaged encoder was moved relative to a relief grating scale with a pitch of 3.2 μm. Good sine curves were obtained. By putting the I_A and I_B signals on the horizontal and vertical coordinates, respectively, we obtained Lissajous curves (Fig. 8(b)). The two signals were phase-shifted by almost 90°. The revolution direction corresponded to the movement direction of the grating scale relative to the encoder. One revolution corresponded to a 1.6-μm displacement, or half the grating pitch and in term of revolution angle of a 7 mm-diameter scale, it corresponds to 0.028 degrees. The detected Z signal is shown in Fig. 9. A steep Z signal is important, because the steeper the Z signal is, the more precise the slicing

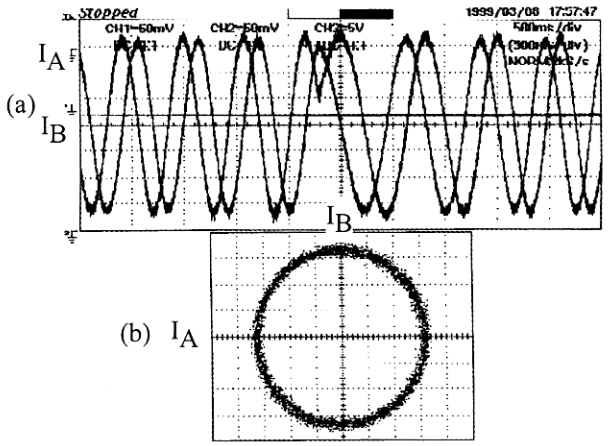


Fig. 8 Signals. (a) Sinusoidal intensities I_A and I_B from the two-segment photodiodes when the tilted encoder was moved while a gap of 700 μm was maintained relative to a relief grating scale with a pitch of 3.2 μm. (b) By putting the I_A and I_B signals on the horizontal and vertical coordinates, respectively, we obtained Lissajous curves .

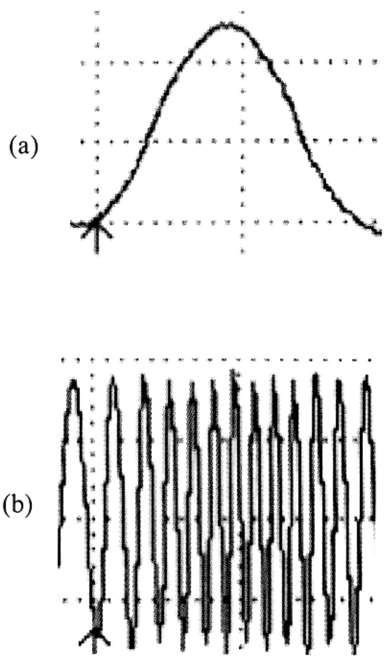


Fig.9 (a) Z signal detected compared with (b) sinusoidal signal obtained from grating.

position is when the Z signal is sliced with a certain threshold value. We expect to further improve the slicing position precision, that is, the Z signal positioning accuracy, by increasing the reflectivity difference between the Z pattern and the other area; for example, by using a scale made of transparent glass instead of silicon.

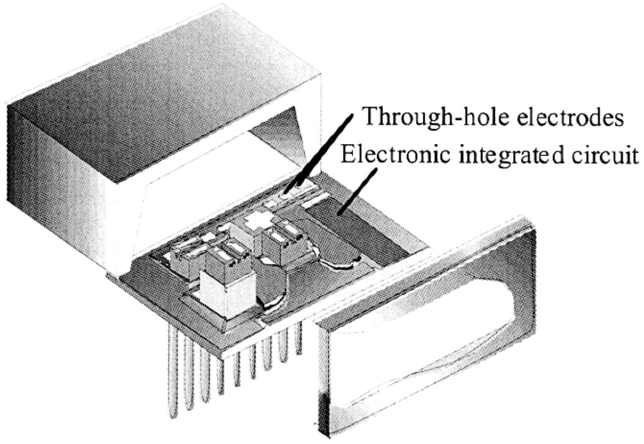


Fig.10 Schematic of the laser encoder combinated with ICs and through-hole electrodes, which can be formed on the PLC chip.

CONCLUSION

Our encoder exhibited a longer life span and lower consumption power than the monolithically fabricated encoder although it is somewhat large. Also, it should be considered that miniaturization leads to a complicated tangle of wires as can be seen in Fig. 2(b). A new subject like this occurring as MEMS progresses, should be considered in the future. So it will pave the way for combination with ICs, which can be formed on a PLC chip and through hole electrodes as schematically shown in Fig. 10.

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