Letter

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Polarimetric linear absolute position encoder

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Abstract: Optical encoders based on measurement of the axis-angle of linear polarizers offer high resolution and moderate accuracy, but are usually restricted to rotary measurement. We show that annular polymer sheet polarizer materials can be sheared into rectangular tapes, with a polarizing axis that varies linearly along the tape. This makes possible the construction of polarimetric linear absolute position encoders. We demonstrate also sheared polymer birefringent retarders, which function similarly, potentially with cost and size-flexibility advantages.

Keywords: linear encoders; optical polarization; polymer retarders.

1 Introduction

Polarimetric *rotary* encoders have been popular for several decades [1]. The variation in light intensity transmitted through two polarizers as a function of angle θ between them varies nominally as $\cos^2\theta$, allowing simple, essentially calibration-free angle evaluation from two or more intensity samples with different phases. Sheet polarizers are available at low-cost and in large sizes following development for use in LCD mobile phone displays and TV screens.

However, we know of no *linear* encoder based on a similar, simple polarimetric effect. One possible way to fabricate linear polarimetric encoders would be via microstructured surfaces and nano-imprinting techniques [2, 3], which can be used to make arbitrary angle polarizers. Here we describe the initial demonstration of an alternative technique using sheared polymer polarizers.

2 Sheared linear polarizers

In our development of rotary polarimetric encoders without the ambiguity caused by the polarizer's 180° symmetry, we fabricated narrow circular and semi-circular annuli from sheet polarizer material [4]. Figure 1A shows such a semicircle of polymer polarizer. The red arrows depict the polarizing axis at a few points around the circumference. Applying tension as shown and pulling apart the ends of the annulus should shear it into a long, narrow rectangular tape (Figure 1B). The lines of Figure 1B indicate the deformation of the local polarizing axis. This deformation results in a linear rotation of local polarizing axis along the tape. It is clear from the red arrows that the polarizing axis makes a 180° rotation along the tape; there is no ambiguity in polarizing angle. Figure 1C shows the variable brightness appearance of the tape when illuminated by linearly polarized light. The shearing process will be easier, the smaller the width/diameter ratio of the original annulus.

3 Fabrication

A motorized plate-glass platen and scalpel blade mounted on an XYZ-stage were used to cut circular annuli with various diameters from 50 to 150 mm out of polymer sheet polarizer. These were then split into semi-circles, clamped and axially tensioned as in Figure 1A. The polarizer then arranges itself into a periodic wave geometry (Figure 2), or if also twisted, into a spiral structure.

The tensioned tape was heated in hot-air to around 100 °C, relaxing it into a planar rectangular shape. A quick observation of the tape against the polarized light of an LCD computer monitor displaying uniform white light indeed showed one cycle of characteristic bright/dark intensity, exactly as in the drawing of Figure 1C.

4 Opto-electronic position evaluation

We focus first on a 120 mm diameter, 4 mm wide annulus cut from 200 µm thick low-cost polarizer similar to now-obsolete Polaroid/3 M HN38 material, resulting in a 180 mm long rectangular polarizing tape. The optical readout system used consisted of a surface-mount 525 nm LED shining through the tape onto three Si-pin photodiodes A,B,C

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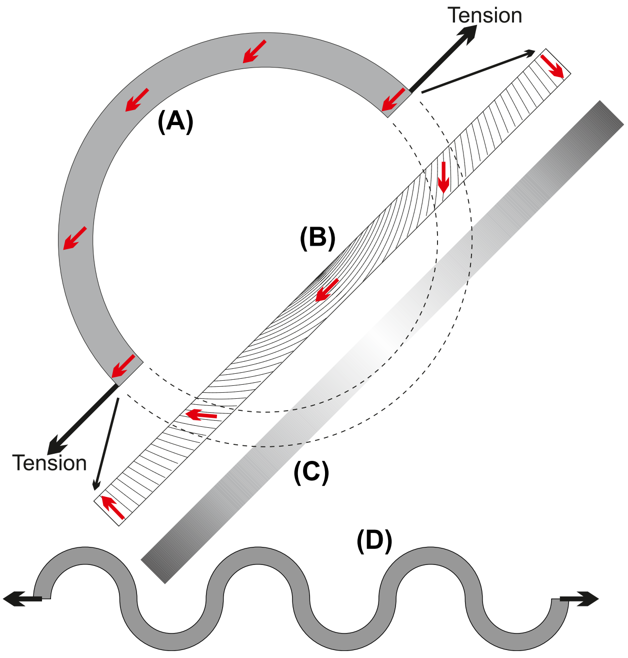

Figure 1: A narrow semi-circular annulus (A) can be sheared by tension into a rectangular tape, retaining the linear variation of polarization axis (B). Viewed in polarized light there is one visible dark/light cycle (C). Serpentine forms could show multiple dark/light cycles (D).

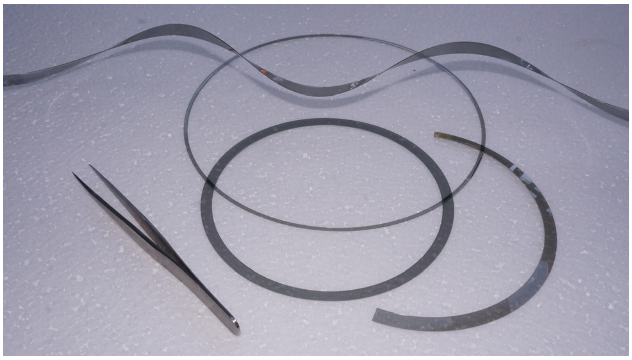

Figure 2: Full- and semi-circular annuli cut from sheet polarizer, one tensioned ready for stretching.

(Hamamatsu S8729). Each photodiode had a piece of linear polarizer glued to it, these arranged by eye at approximately 0°/120°/240°. Transimpedance amplifiers using rail-to-rail operational amplifiers, a 16 bit analog to digital converter and microprocessor completed the data-acquisition. This is the same detector configuration used in ref. [4]. The microprocessor also controlled a 200-step stepper motor with micro stepping driver.

The LED source and detector array were mounted on a motor-driven recirculating-ball slider with a 300 mm precision ground rail. The polarizer strip was tensioned but otherwise unsupported, allowing scans of transmitted intensity along its length. A straightened semi-circular segment produces one offset cosine intensity cycle, with each channel A, B, C separated by approximately 120° in phase. Small differences in sensitivity were corrected in software with one-time scale-factors. Quadrature signals I, Q were generated from the three operational amplifier output voltages using the Clarke transform [5]: $I = -\tfrac{1}{2}A + B - \tfrac{1}{2}C$, $Q = -0.866A + 0.866C$ and then the angle was calculated using the microprocessor's C language arctangent function atan2(Q,I) in floating point arithmetic. Angle was converted to linear position by assuming linear operation and adjusting for the correct slope mm/°phase. No further calibration was applied.

Figure 3 shows the basic linearity of the method, albeit with modest errors. The insert plots the deviation from perfect linearity, here approximately ±0.7% of full-scale. We believe that some of the error comes from differential intensity variations from light scatter at blemishes of the tape passing the three, spatially separated photodiodes and from off-normal geometry of the three beams. A superior detector would consist of many interspersed photodiodes with polarizers at 0°/120°/240° or other angles fabricated as a monolithic OptoASIC. Such devices have been manufactured by Advico [6] and others [7]. Note that these devices only detect linear states of polarization. The addition of pixelated optical retarders to additionally estimate ellipticity and perform a complete state of polarization analysis is expected to further reduce errors. Birefringent polymer retarders using nano-imprinting [8] have been demonstrated, which could be used for this.

5 Sheared linear retarders

A second set of experiments was performed using transparent optical retarders instead of polarizers, where similar performance can be obtained. We used polypropylene A4 “sheet protectors,” clear plastic envelopes used for filing documents. Like most plastic sheets these foils show linear birefringence. If semi-circular annuli cut from these foils are plastically deformed as above, the resulting tape should function as a retarder of linearly varying retardation axis.

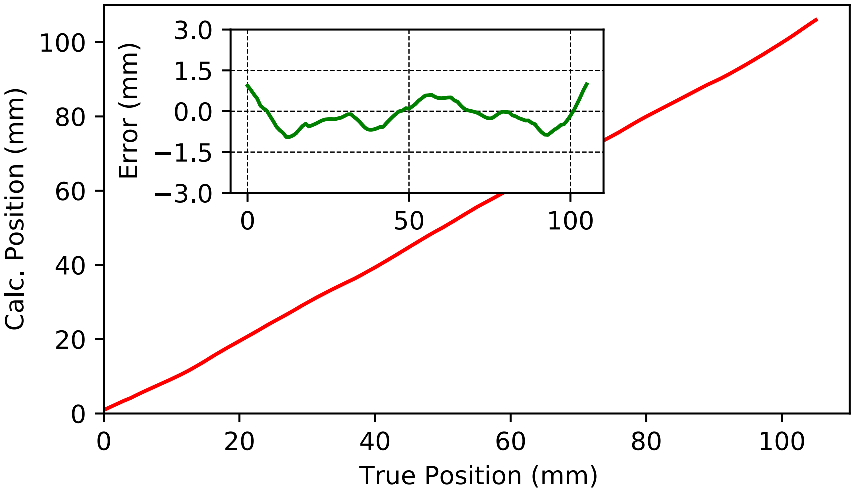

Figure 3: Linear encoder output using a sheared polarizer. The insert shows the departure from perfect linearity.

These materials deform more easily than most polarizers as they are thinner (~70 µm). By clamping the annulus and applying tension the foil sheared easily into a straight rectangular tape without thermal softening.

To determine the retarder's axis angle the source should be polarized, but the multi-phase polarized detector can remain as above. If the input state of polarization (SOP) is linear (e.g. H-horizontal) and the retardation only 100 nm, ~$\lambda/5$ for the green light used here, the output SOP traces out a small figure-of-eight on the Poincaré sphere representation as the retarder axis rotates (Figure 4A). H, V, P, Q represent horizontal, vertical, +45°, −45° orientated linear states respectively. L and R are left- and right-handed circular states. Linearly polarized detectors spaced around the equator then see a low modulation depth, and more importantly large intensity differences between the channels A, B, C. We chose therefore to use an approximately circularly polarized input SOP. On rotation of the retardation axis along the length of the plastic tape the output SOP traces a small-circle of constant ellipticity (or latitude) on the sphere (Figure 4B). Hence the three linear detectors should see phase shifted signals of similar amplitude. A quarter-wave retarder tape would give a SOP running around the equator, and hence 100% modulation depth for all detectors.

Figure 5 shows the raw A, B, C signals along a 100 mm length of the tape, with ~80% modulation depth. As with the polarizers, the signals can be evaluated as an angle, and hence as a position along the tape. Figure 6 shows a scan along such a tape, with errors bounded by about ±0.7 mm.

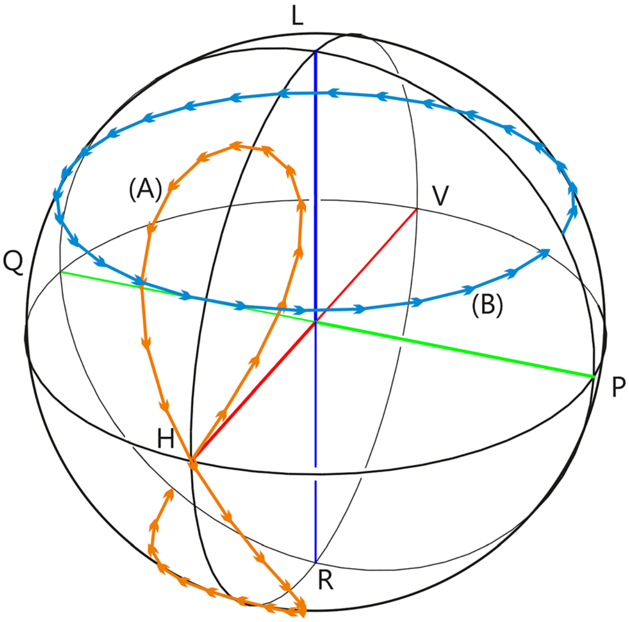

Figure 4: An input linear SOP (H) passing through the sheared retarder produces the figure of eight locus on the Poincaré sphere (A) as the retardation axis rotates along the rectangular tape. An input circular SOP (L) transforms instead into an elliptical SOP of approximately constant ellipticity (B).

If ambiguity due to two or more intensity cycles is not problematic, or is even desirable in a particular application, a full circular segment of polarizer or retarder can be used. Similarly, serpentine forms (Figure 1C) can be plastically sheared into straight tapes and used where multiple transmitted intensity cycles are desired.

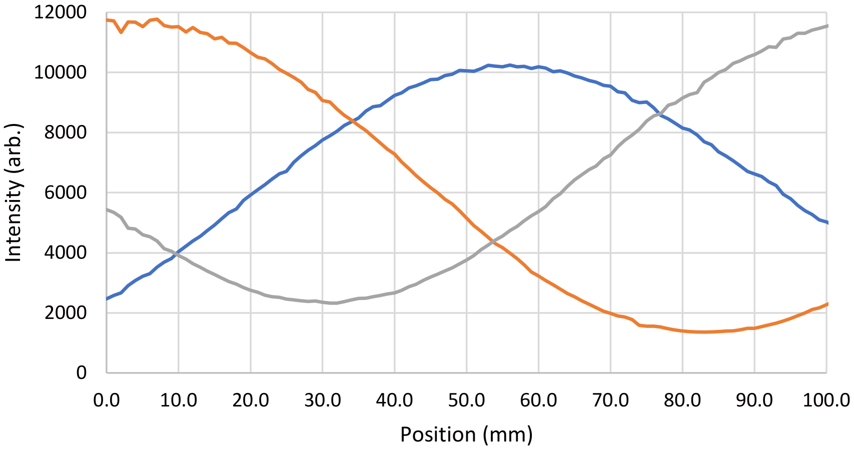

Figure 5: Raw polarized detector outputs using a sheared polymer film as a weak optical retarder.

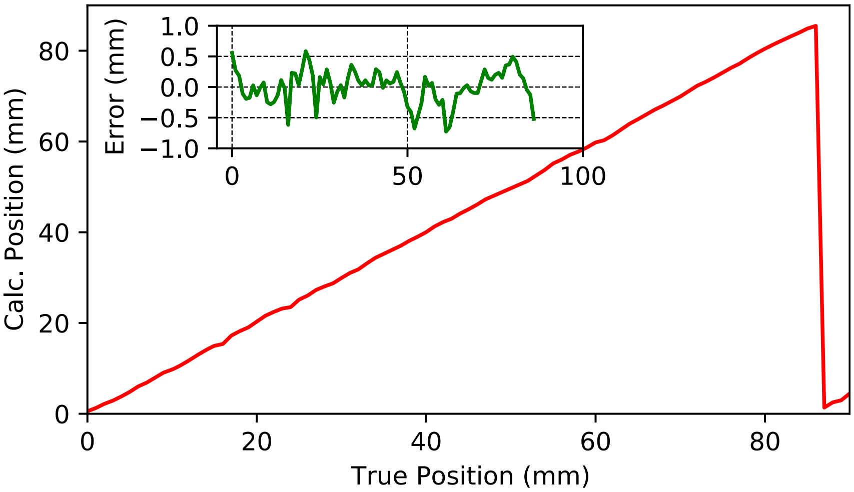

Figure 6: Linear encoder output using a birefringent retarder cut from a transparent document protector. The insert shows the departure from perfect linearity.

6 Discussion

Linear absolute encoders can be based on potentiometers, magnetized films, coupled printed circuit coils, differential transformers, acoustic time of flight and several other techniques. Some techniques have a performance or cost advantage in a particular application area. For instance, multitrack optical absolute encoders can offer better than 15 bit accuracy, but at very high cost. Coupled printed circuit transformers perform well in dusty environments and can be fabricated in almost arbitrary size, but suffer from electromagnetic interference and the thermal expansion coefficient of circuit board materials. Aimed primarily at low-cost applications, our initial demonstration of a polarimetric technique has most similarity to linear potentiometers. Our demonstrator's ~±1% accuracy compares well with the typical ±1% to ±3% linearity of low-cost potentiometers [9]. These, however, suffer from friction, wear and a limited life. One issue concerns the cutting of large semi-circles from sheet polymers which will be wasteful unless a range of different size encoders is required.

Several of these techniques can perform even in extreme environments. Based on polymer polarizers and retarders, the polarimetric technique described here is unlikely to offer such ruggedness. Nevertheless, ruggedness and thermal stability should be improved by encapsulating the polymer tapes between glass sheets, which will also reduce the effect of surface blemishes. The result can be rigid or flexible, as required by the application. The thermal deformation technique may even be applicable to polarizers fabricated in glass substrates. Our demonstration used an LED source and a detector array on opposite sides of the polarizer. Alternatively, source and detectors can be located on the same side, with a mirror or diffuse reflector behind the tape. Tapes could even be overlayed onto an incremental optical encoder to give both incremental and absolute outputs.

Our experiments with sheared birefringent plastic foils gave results comparable to those of polarizers. Both materials show high spatial-frequency errors which could be due to surface scattering or to locally-variable strains caused by asperities during the shearing process. Perfection in cutting out the annuli before shearing is likely to be significant in reducing these errors. The retardance of the plastic foils used was not ideal and they have certainly not been manufactured with retardance uniformity in mind. Accurate ¼-wave polymer retarders are available which might improve modulation depth and uniformity. However, the very low cost and large available size of ordinary sheet plastic foils is attractive.

We have shown that annular polymer polarizers and retarders can be plastically deformed into rectangular tapes, to enable a family of modest accuracy, linear absolute position encoders. The ideal optical detector would be an OptoASIC containing many sub-detectors with an array of linear polarizer orientations, some overlaid with birefringent retarders to allow full state of polarization determination. The encoders are interesting in being absolute, not incremental, configurable even in meter dimensions on flexible or rigid substrates and potentially of low cost. Wear-free non-contact operation is innate, and readout heads could be remote, fiber-connected and fully optical, without metallic elements or active electronics.

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