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Optical delay line using rotating rhombic prisms

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ABSTRACT

We propose a robust and efficient delay line using an ensemble of rotating rhombic prisms. Delay lines relying on rotating elements provide fast and stable operation. Optical systems using rhombic prisms are quite easy to align since these prisms are efficient even when slightly misaligned. Optical delay lines with a single rotating element usually have a poor duty cycle and show large nonlinearity in the variation of the optical path lengh with the angular position. Our delay line improves over existing technology by using off-centroid rotation and reinjection. Off-centroid rotation allows the use of multiple prisms and, by optimizing the conditions of operation, the duty cycle is increased and the nonlinearity is decreased. The duty cycle and repetition rate are further increased by reinjecting the incoming ray towards the delay line when it is not first intercepted by the prism ensemble. We have designed and built such a delay line using five prisms. The experimental device was tested at 2000 delay scans per second and provided a duty cycle larger than 80% with about 5% nonlinearity. Higher delay scan rates are easily achievable with this technology. The delay line was introduced in a time-domain optical coherence tomography system and example of imaging of biological tissue is provided.

Keywords: Delay line, low-coherence interferometry, optical coherence tomography, biomedical imaging

1. INTRODUCTION

The development of optical delay lines has been quite active during the last decade, especially in the field of time-domain optical coherence tomography (TDOCT) where one is striving for high scan repetition rates to achieve real-time imaging. Important parameters for optical delay lines are: scan range, scan velocity, duty cycle, linearity, dispersion and polarization effects. For the mass production of optical delay lines and/or for continuous use in medical or industrial environments, there are two important additional criteria often less considered: the ease of optical alignment and the robustness of the delay line.

TDOCT measurements are generally performed with a scan range of a few millimeters and require a repetition rate of at least a few kilohertz to allow real-time imaging. A detailed review of optical delay lines used in TDOCT has been published by Rollins and Izatt.[1] The simplest designs rely on the translation of a retroreflective element or on galvanometer-mounted retroreflectors. These generally suffer from low scanning repetition rate and nonlinearity. Higher stability and higher repetition rates can be obtained from uniformly rotating elements. Examples of such designs are the use of a multi-segment CAM,[2] of a cube rotating around its center-of-mass,[3] of rotating parallel mirrors,[4] of an ensemble of prisms on a rotating wheel,[5] and of a rotating parallelogram prism.[6] These designs suffer to various degree from one or many of the followings: low-duty cycle, nonlinearity, difficult alignment, or lack of robustness. Other designs are based on the use of fibers. One such approach relies on the stretching of a fiber winded around a piezoelectric plate or cylinder whose expansion induces a variable optical delay.[7] Such a design can achieve high scanning rates but suffers from high power requirements and birefringence effects. A celebrated approach based on the use of a grating was first proposed by Kwong et al.[8] and later improved by Tearney et al.[9] The optical alignment is delicate because many parameters must be considered simultaneously. Mechanical stability is questionable for an eventual use in an industrial environment or for achieving high absolute accuracy.

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In this paper, we propose a novel optical delay line that relies on the use of an ensemble of rhombic prisms on a rotating disc with reinjection of light. The rhombic prism is a very forgiving optical element since it can be used even when slightly misaligned. An optical delay line using rhombic prisms is thus very easy to assemble and quite robust. By having the ensemble of prisms rotating on a disc, one can obtain a stable and high repetition rate with commercially available high-speed rotating motors. Additionally, by using reinjection of the optical ray and by optimizing the position and orientation of the prisms, one can obtain good linearity and high duty cycle.

The case of a simple delay line with a single rhombic prism is first considered in Section 2 as an introduction to the discussion of the optimized delay line using many prims. The later is then described in Section 3 along with experimental results including optical coherence tomography imaging. All the modeling in this paper can be expressed with analytical expressions. These are rather lengthly and are omitted here for briefness. All the results in this paper are evaluated using the Rayica ray tracing software (www.opticasoftware.com), detailed analytical expressions will be published elsewhere.

2. DELAY LINE WITH ONE ROTATING PRISM

A simple delay line can be obtained with a single rhombic prism rotating around its centroid. This design is nevertheless not very efficient but its analysis provides guidelines for improvement.

Figure 1 illustrates a retroreflective delay line composed of a rhombic prism rotating in the $X - Y$ plane around an axis passing through its centroid, an optical coupler to both deliver and collect the light, and a mirror to insure retropropagation. The angular position of the prism is determined by the angle θ between the front face of the prism and the X-axis, defined positive in the counterclockwise direction from the X-axis. With the proper conditions (cases b, c, and d of Fig. 1), a ray exits the optical coupler towards the rhombic prism along an axis at a distance L_{in} from the centroid and travels to exit the prism parallel to its initial direction. It is then retropropagated by the mirror towards the prism to finally be collected by the optical coupler. The two faces of the prism that are used for reflection are metallized. Note that the robustness and ease of alignement is insured by the rhombic prism since when the mirror is well oriented, the prism can be slightly misaligned and the optical ray will still exit through the optical coupler. Under different conditions, the ray is not intercepted by the prism (cases a and f) or the ray does not exit parallel to its initial direction (case e).

As the prism rotates, the optical path length varies with the angle between the ray and the front face. In fact, the detailed analysis shows that the path length only depends upon the orientation of the prism and not upon the entry point, as long as the conditions are met for the ray to exit the prism correctly. The scanning range is determined by the angular range over which the ray enters and exits the prism correctly. This varies with the refractive index of the prism and the distance L_{in} between the ray axis and the rotation axis. In Figure 2, we consider a BK7 rhombic prism (5 mm thickness between faces, inner angle 45^o) rotating around its centroid for various distances L_{in} of the incoming ray (wavelength 1.3 microns). For each value of L_{in}, the angular range over which the prism intercepts the incoming ray is contained within the grayed region. Dark gray indicates the range over which the ray enters the prism and exits parallel to its initial direction (cases b, c, and d of Fig. 1), it thus identifies the usable range. The light gray region corresponds to the case where the prism intercepts the incoming ray with the ray exiting in a direction different from its original direction (case e in Fig. 1).

Figure 2 shows that the duty cycle is far from optimal. It reaches a maximum value of 41% for $L_{\text{in}} = 3.5$ mm. In this case, the optical path lengh variation is 8.4 mm (single pass from the optical coupler to the mirror). Unfortunately, this variation in path length is not linear with the angle, the nonlinearity being 42% (variation of the derivative over the maximum value of the derivative). These numbers are similar to those often obtained for delay lines relying on the rotation of a single optical element and are not ideal for the design of an TDOCT delay line.

Improvement to this basic design can be obtained in a two-fold manner. Firstly, a better control of the angular range over which the prism is used can be obtained by having the prism rotate on an axis not centered on its centroid and by optimizing its orientation. This also allows the use of many prisms. This contributes to improve both the duty cycle and the linearity. Secondly, when the ray is not intercepted by the prism, it can be redirected and reinjected from a different direction. This also contributes to improve the duty cycle. Such an optimized delay line is discussed in the next section.

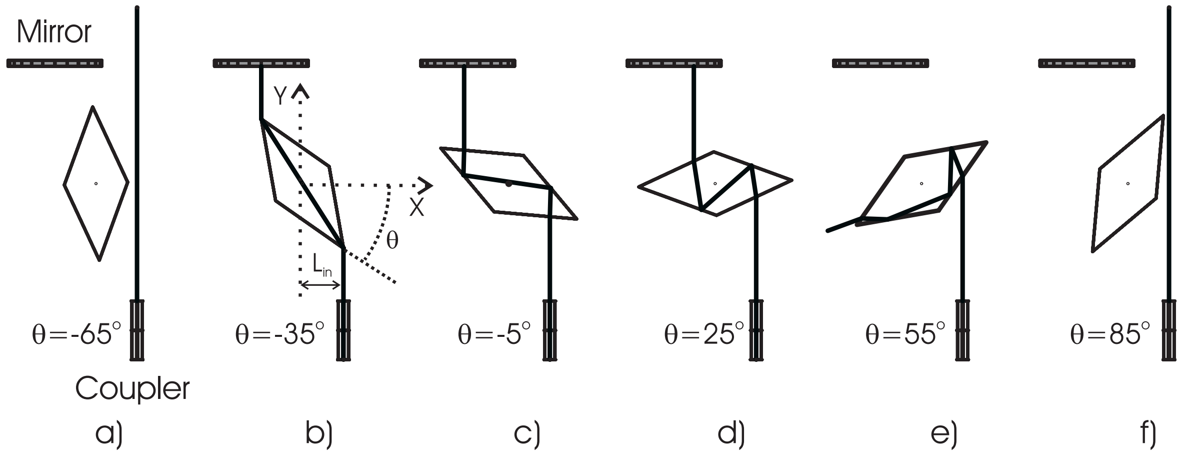

Figure 1. Ray tracing for the simple optical delay line showing various orientations of a rhombic prism rotating around its centroid. The prism is made of BK7 glass, has an inner angle of 45 degrees, and has a thickness of 5 mm between opposite faces. The wavelength is 1.3 microns.

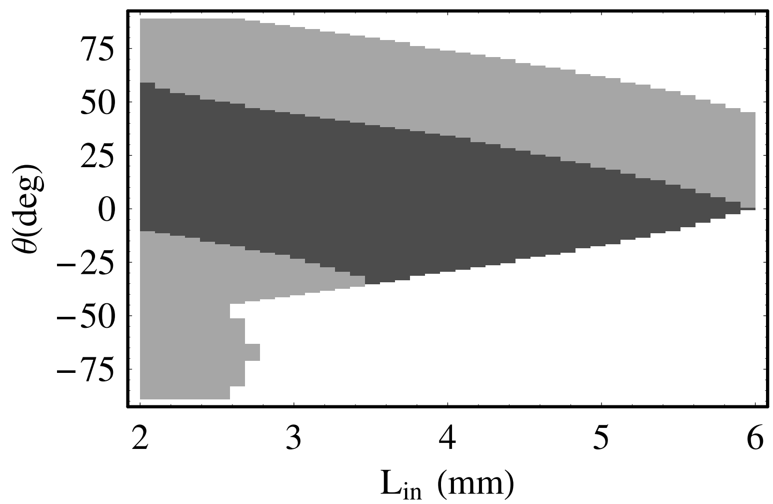

Figure 2. Range of angles over which the prism intercepts the incoming ray for various distances L_{in} from the rotation axis for the delay line considered in Fig. 1. The light gray indicates the range over which the ray exits in a direction different from its initial direction while the dark gray indicates the good region over which the ray exits parallel to its initial direction.

3. DELAY LINE WITH AN ENSEMBLE OF ROTATING PRISMS

Figure 3 shows an optical delay line with five rhombic prisms rotatable around the center of a disk. This setup relies on off-centroid rotation and reinjection to increase duty cycle and reduce nonlinearity. The five prisms are placed at equal angular intervals with their centroid located at a distance R from the axis of rotation. The angular position of a prism is determined by the angle θ between a radial line going through its centroid and the X-axis, the angle θ being defined positive in a counterclockwise direction from the X-axis. The orientation of each prism relative to the disc is determined by angle θ_0 between the front face of the prism and a radial line passing through the centroid of the prism, θ_0 being defined positive in a counterclockwise direction from the radial line.

Two modes of operation are effective during a rotation: direct and reinjection. Figure 3a) illustrates the direct mode in which a ray exits the optical coupler, goes through the prism, is reflected by the mirror to follow the exact inverse path to be collected by the coupler. Figure 3b) illustrates the reinjection case where the ray is reflected by a first mirror towards a prism and then reflected by a second mirror to return by the inverted path towards the coupler.

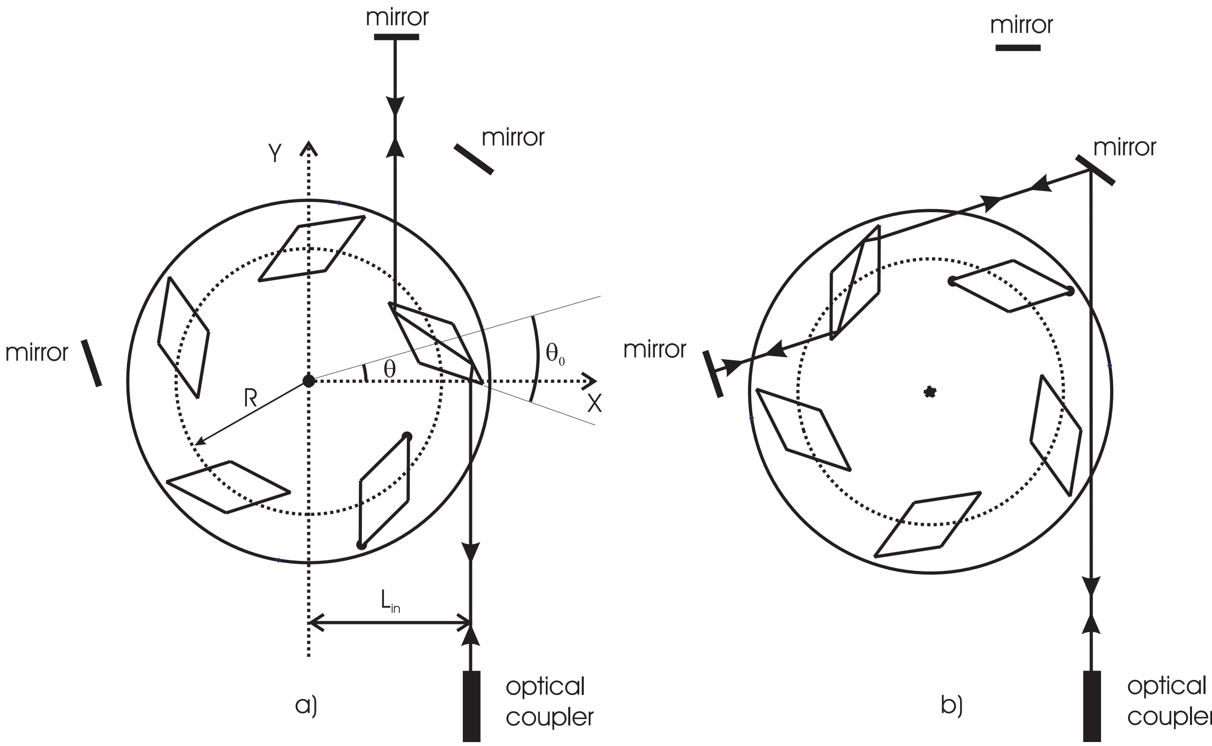

Figure 3. Optical delay line with five rotating rhombic prisms with a) the ray entering a prism directly and b) a ray being redirected before entering a prism.

The delay line in Fig. 3 contains five prisms and one reinjection mirror, but delay lines could be built with different number of prisms and reinjection mirrors. For a given number of prisms, many parameters can be adjusted to obtain an optimal performance: the radius R, the distance between the incoming ray axis and the rotation axis L_{in}, and the orientation of the prisms relative to the disc θ_0. For the same BK7 prisms considered in Section 2 (thickness of 5 mm between faces, internal angle 45^o), guidelines to find the optimized parameters can be obtained from the results of the previous section. Figure 2 suggests that the ray should begin to intercept a prism at a distance of about 3.5 mm from its centroid, and stop being intercepted at a distance of about 6 mm from the prism centroid. Additionally, data not shown Section 2 indicate that the nonlinearity is reduced when the angular range used for each prism is centered around an incidence angle of 17^o (angle between the normal of the front face of the prism and the incoming ray, defined positive in the counterclockwise direction). Note that with these parameters no metallization of some faces of the prism is necessary, everything occurs through total internal reflection. The optimal parameters provide a path length variation of 4.3 mm (single pass, from the coupler to the retropropagating mirror). Each prism is used twice per revolution over an angular range of about 33° each time. Thanks to re-injection, the resulting duty cycle of the delay line can theoretically exceed 90%. The nonlinearity is rather small, being about 7.5%. This represents a huge improvement over the delay line of Section 2.

Such a delay line was built and used in an optical coherence tomography system using a Covega superluminescent diode operating at a wavelength of 1.31 microns. The tested unit was performing 2000 delay scans per second, this was mainly limited by our available electronics, much higher rates being achievable. The resulting single-pass (from coupler to retropropagating mirror) optical path length l_p variation for a single prism as a

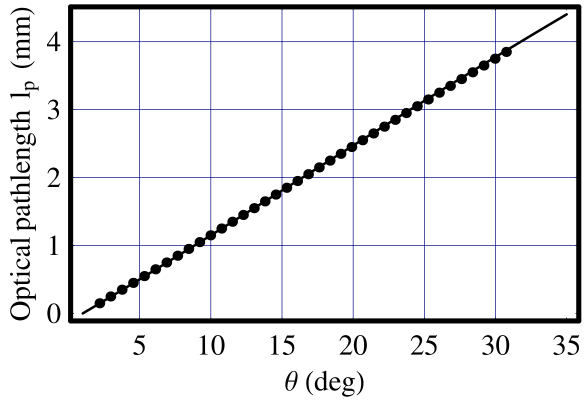

Figure 4. Variation in optical path length with the angular position for one prism of the optimized delay line described (see text). Continuous line is obtained with modeling and the points are measured with the experimental unit.

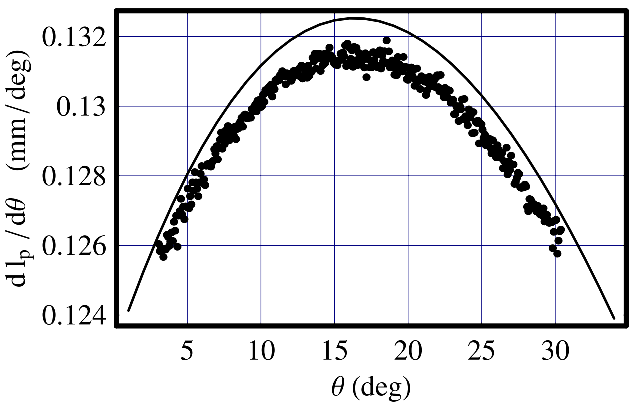

Figure 5. Variation of the derivative $dl_p/d\theta$ over the usable angular range for a prism of the optimized delay line (see test). Continuous line is obtained with modeling and points are measured with the experimental unit.

function of the angle θ is shown in Fig. 4 along with the modeled variation. The experimental duty cycle is about 80%. This is slightly less than expected since the usable angular range is reduced due to the finite width of the collimated beam travelling through the delay line and due to some imperfections at the corners of the prisms.

Figure 5 illustrates the variation of the derivative $dl_p/d\theta$ over the usable angular range of a prism. There is some variation in the experimental measurements. This is due to the fact that measurements were performed in a Michelson configuration which is sensitive to various environmental fluctuations and that measurements taken at slightly different times were combined to evaluate the derivative. The slight discrepancy (less than 1%) between the experimental and modeled results are attributed to difference between the nominal and real prism thicknesses. Note that the reduced angular range also provides a reduced nonlinearity of about 5%.

The proposed delay line can be assembled in a compact unit. This technology, which is currently being patented, is commercialized through Novacam Technologies (www.novacam.com). Figure 6 presents the TDOCT image of a finger nail obtained with a compact system built by Novacam Technologies.

4. CONCLUSION

In this paper we have described a new optical delay line that is robust and easy to align in addition to showing excellent characteristics in terms of duty cycle, linearity and rapidity. This was achieved thanks to the forgiveness

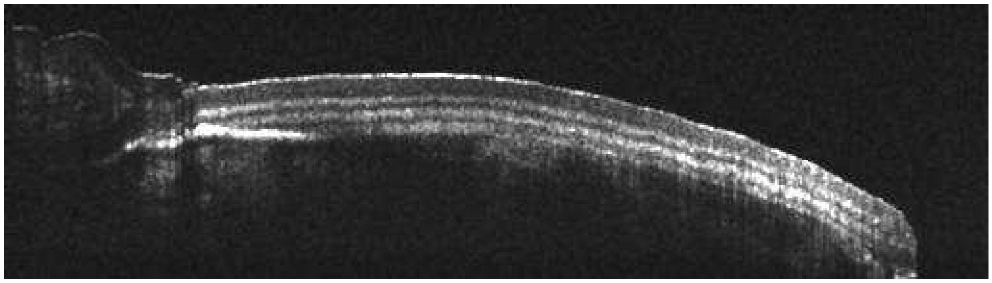

Figure 6. TDOCT image of a finger nail.

of rhombic prisms and with the use of off-centroid rotation and re-injection. We also presented experimental results showing the efficiency of the proposed delay line when integrated in a TDOCT system.

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