Synopsis of "Risley Prism Beam Pointer"

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SUMMARY

This synopsis describes a beam director using a three-element Risley prism mechanism. Key results of the work are presented as well as potential applications. Similar work is considered and compared.

1. INTRODUCTION

Risley prisms are wedged optics, usually used in pairs, to redirect optical beams. A typical Risley prism pair is shown in Figure 1.

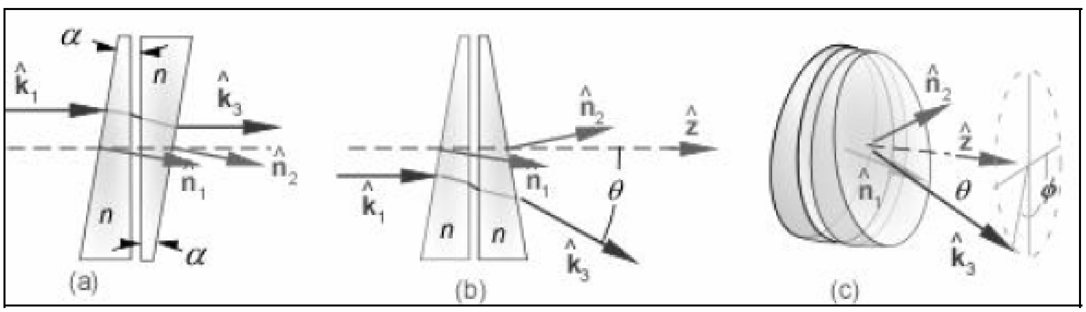

Figure 1. Risley prism pair

The incoming light, given by vector $\mathbf{k}_1$, enters the prism pair on the left, experiences a series of refractions and redirections given by Snell's Law, and emerges from the Risley pair with vector $\mathbf{k}_3$ on the right. As shown in part (a) of Figure 1, if the prisms have their wedge normals aligned, there is just a translation of the output beam, $\mathbf{k}_3$, with respect to the input beam, $\mathbf{k}_1$. If the wedge normals are pointed opposite each other (b), the output beam experiences a maximum elevation (θ) deviation. The ability to control azimuth (ϕ) is provided by rotating the prism pair together, as seen in (c). The direction cosines for a beam emerging from such a Risley prism pair are shown in Figure 2.

$$\begin{bmatrix} k_{3x} \\ k_{3y} \\ k_{3z} \end{bmatrix} = \begin{bmatrix} \cos\phi\sin\theta \\ \sin\phi\sin\theta \\ \cos\theta \end{bmatrix} = \begin{bmatrix} \beta\sin\alpha + \cos\phi'\sin\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \\ \sin\phi'\sin\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \\ (1+\beta\cos\alpha) + \cos\alpha\left[\sqrt{1-n^2+\gamma^2(\phi')} - \gamma(\phi')\right] \end{bmatrix}$$

$$\beta = \sqrt{n^2 - \sin^2\alpha} - \cos\alpha$$

$$\gamma(\phi') = \cos\alpha + \beta\left(\cos^2\alpha + \cos\phi'\sin^2\alpha\right)$$

Figure 2. Direction cosines for Risley prism pair in terms of prism orientation

The Risley pair can be used to direct a light beam to any elevation angle and azimuthal angle, limited only by the wedge angle of the prisms, α, and given by the azimuthal rotation between the prisms, ϕ'.

This synopsis evaluates recent work done at Ball Aerospace on a 3-element Risley prism assembly. The paper, "Risley Prism Beam Pointer," by Ostaszewski, et al.[1], describes the achievements of the development effort, as well as potential applications for such a device.

2. KEY RESULTS

2.1. System Architecture

This paper points out the common drawbacks of Risley prisms:

1. Singularity – excessive prism rotation speed for angles approaching on-axis (boresight)
2. Nonlinearity – non-linear control equations require local linearization and/or look-up tables
3. Tolerances – wedge angle, alignment, temperature, & pressure all affect alignment
4. Blind Spot – boresight dead zone on axis

To avoid problems with singularity and the blind spot, the authors incorporate a third Risley prism. This third prism introduces an additional degree-of-freedom that pushes the boresight off-axis. Continuous orientation of the third prism allows tracking through the boresight. However, introducing the additional prism now makes the system underconstrained and means the control system must deal with an infinite number of solutions for the same elevation and azimuth target angles.

Key design parameters for this Risley prism mechanism are summarized in Table 1.

Parameter	Value	Comments
Clear Aperture (CA)	100 mm	Optics must be oversized to allow for steering
Wavelength	1550 nm	Silicon optics
Wedge angle	7°	Affects range and resolution
Field of Regard (FOR)	±72°	Achieved with material choice, wedge angle, and thickness
Pointing Resolution	100 μrad	Limited by optical encoder resolution
Pointing Accuracy	1 mrad	Depends on thermal environment
Slew Rate	10°/sec	Provided by the torque motors
Control Bandwidth	23 Hz	Includes mechanical slew and settle time
Optical Throughput	85 – 96%	Even with AR coatings, back-reflections were an issue
Wavefront Quality	Diffraction-limited	Surface figure error on wedge faces $<\lambda/50$ rms
Operational Temperature	-50 – 70 °C	Allowance made for CTEs of different materials

Table 1. Summary of performance parameters for Risley Beam Pointer (RBP)

2.2. Optical Design

As indicated in the table above, this system is to be used at 1550 nm. The wavefront quality is to be such that diffraction-limited performance is achieved. The dominant wavefront aberration is astigmatism (anamorphic magnification). Additionally, it has polarization-dependent transmission and stray light requirements (details not specified in paper).

To avoid Fresnel reflection losses at the air-silicon interfaces, an anti-reflection (AR) coating is used. This, however, can introduce phase changes to the transmitted light. A phase change means there is polarization retardation to account for. The authors refer to a proprietary AR coating that limits back-reflection to a few percent. The phase retardance analysis predicts the coatings do not appreciably distort the polarization states. It is noted that some references on Risley prism design eschew the use of three prisms due to the problems encountered with these back reflections[2].

The aspect ratio of the optics affects two competing priorities. To minimize beam walk, we want thin optics. However, it is difficult to achieve good beam quality with thin optics. Working with Coastal Optical Systems (http://www.coastalopt.com/), the authors are able to show surface figure error of λ/50 rms, to as low as λ/200 rms (λ = 1550 nm). This surface figure error does not change appreciably after bonding the optics in their mounts. The transmitted wavefront error (WFE) for the three-prism assembly over a 100-mm clear aperture (CA) is λ/13 rms for all pointing angles. Over a 50-mm CA, the transmitted WFE is <λ/20 rms. Thus, the assembly maintains diffraction-limited performance over its entire field-of-regard.

Because different parts of the refracted beam go through different thicknesses of refractive material (silicon, in this case), anamorphic magnification is unavoidable. Examples of transmitted beam profiles are shown in Figure 3.

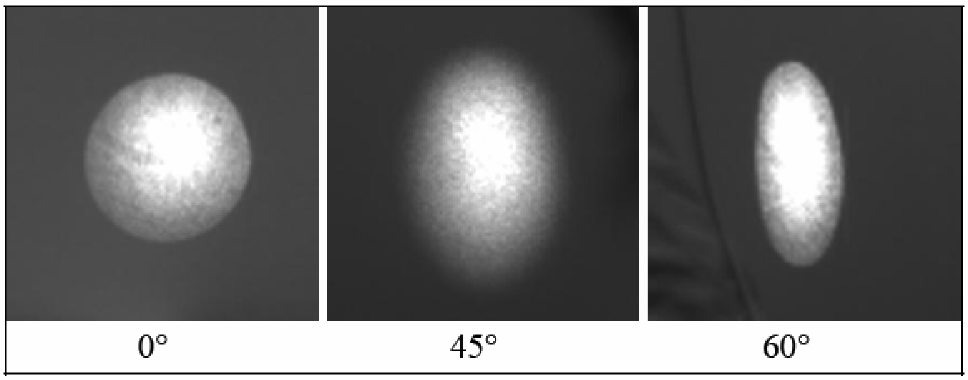

Figure 3. Transmitted beam profiles at different deflection angles

In the Risley prism system, the beam is thus compressed or expanded in the direction of deflection. When viewed along the propagation vector, the beam footprint is always a geometric projection of the beam at the other side of the planar interface. Because of this geometry, the signal received at an aperture will decrease as the pointing angle increases. As seen above in Figure 3, at 60° the area of the transmitted beam will be twice as large as the receiver and the irradiance will be reduced by 50% (3 dB).

2.3. Opto-Mechanical Design

The Risley prisms are mounted in individual cells as shown in Figure 4. The prisms are silicon and held in their cells by tangential blade flexure bonded to the sides of the optics.

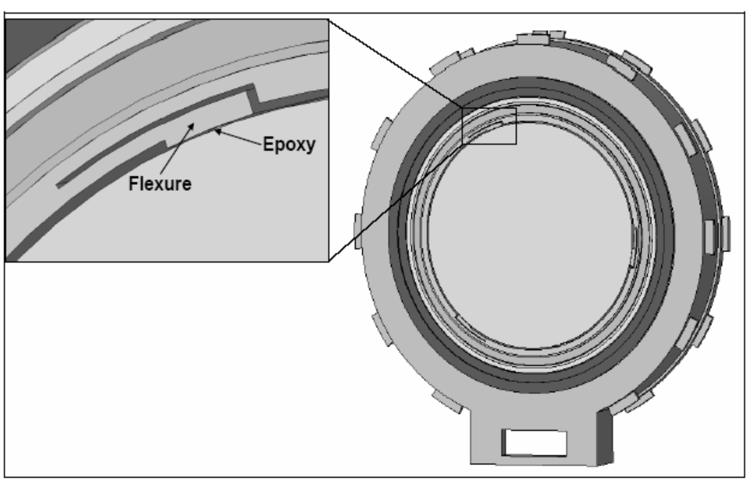

Figure 4. Risley prism optic mount

The tangential blade flexures provide radial compliance, but axial stiffness. The design balances thermo-elastic stresses with a high fundamental frequency (f_o = 500 Hz). The individual optic cells allow the optics to be removed from the assembly during assembly to protect them from damage.

The wedged prisms are mounted in the three independent torque motor drive systems with optical encoder angular position sensors (Figure 5).

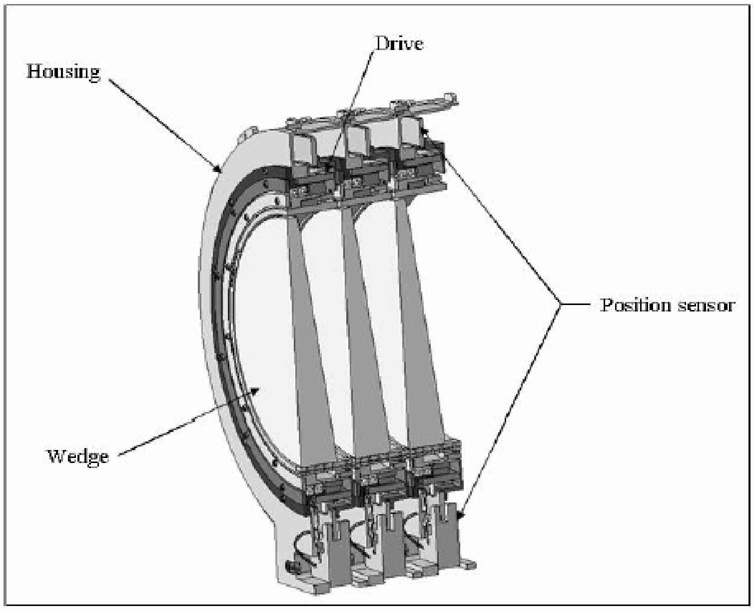

Figure 5. Cross-section of Risley prism mechanism

This mechanism contains a variety of materials – steel (bearings), copper (motor windings), aluminum (housing), glass (optical encoder), titanium (encoder disc hub), and silicon (Risley prisms). To be able to operate over its wide temperature range, compliant design techniques have been employed. (The paper does not provide many details of these designs.)

The control laws and software are summarized in this paper, though more detail is provided in a parallel paper by Sanchez & Gutow[3]. As previously mentioned, adding a third optical element makes the system underconstrained and thus significantly more challenging for the control system. To get around this, one of the three prisms is used as a quasi-static wedge director (WD) while the other two prisms are used in the classic Risley prism pair (RP) manner. The degrees-of-freedom of the system are first reduced by choosing an appropriate WD orientation dependent on the target angle. The RP positions are then solved for using WD position and target angle.

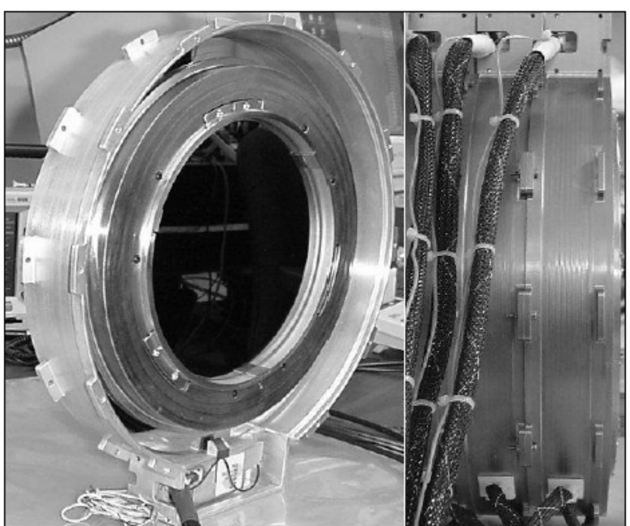

Figure 6. Single Risley prism (left); side view of three-prism assembly (right)

3. APPLICATIONS

As a refractive optic, Risley prisms are less sensitive to mechanical tips and tilts than reflective systems. Thus, fine resolution is easier to achieve. For systems using multiple wavelengths, effects chromatic aberrations and retardance must be considered.

Risley prisms are particularly useful in conformal applications, such as beam steering from aircraft. By not presenting a protrusion or recess to the air stream, the conformal nature of the Risley beam director generates less turbulence. This paper predicts such a system should be able to maintain higher overall wavefront quality than a traditional, reflective, gimbaled telescope because of this.

Other applications for such a Risley prism mechanism include RADAR, LIDAR, and laser communications. The advantages for a spacecraft include compactness and weight savings over traditional azimuth-elevation (Az-El) gimbals. Due to the ability to steer in two dimensions by rotating two masses about only one axis, a spacecraft needs only one counter-rotating mass to account for attitude control[2].

4. CONCLUSIONS

This is a remarkable beam steering mechanism for its field-of-regard (±72°), its resolution (100 μrad), its slew rate (10°/sec), and its operation temperature range (-50 – 70 °C). The additional prism allows smooth motion of the beam anywhere in the field of regard. The additional optical element also presents back reflection challenges that are apparently taken care of using a proprietary AR coating. Work from others suggests a two-element Risley prism assembly has inherent advantages over this approach. Further investigation is warranted.

5. REFERENCES

[1] M. Ostaszewski, S. Harford, N. Doughty, C. Hoffman, M. Sanchez, D. Gutow, R. Pierce, “Risley Prism Beam Pointer,” Free-Space Laser Communications VI, SPIE Volume 6304, 2006.
[2] R. Winsor, M. Braunstein, “Conformal Beam Steering Apparatus for Simultaneous Manipulation of Optical and Radio Frequency Signals,” Atmospheric Propagation III, SPIE Volume 6215, 2006.
[3] M. Sanchez, D. Gutow, “Control laws for a 3-element Risley prism optical beam pointer,” Free-Space Laser Communications VI, SPIE Volume 6304, 2006.