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Practical Considerations of Retroreflector Choice in Modulating Retroreflector Systems

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I. Introduction

Free-space optical communication is often desired between two nodes having different capabilities. For example, a small unmanned aerial vehicle (UAV) has stringent weight and power constraints. Using a modulating retroreflector (MRR) [1] on the UAV shifts most of the power, weight, and pointing requirements to the ground station. Figure 1 shows an unmodulated (CW) laser interrogating a MRR comprised of an absorptive modulator and a retroreflector. If the interrogation beam is within the retroreflector's field of view, the beam will return to the interrogator with data impressed on it.

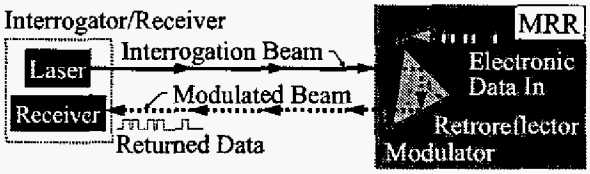

Figure 1: Simple MRR system. Electrical signal is impressed onto the incident CW laser beam.

Optical MRRs were demonstrated [2] before the invention of the laser, but were restricted to short distances and low data rates. Recent advances in optoelectronic devices and free space optics have greatly increased the capabilities of MRR systems.

Several different modulator technologies have been used in MRR systems and compared elsewhere [3]. In this discussion, we compare practical considerations of the two types of bulk optic retroreflectors used in km-range MRRs: corner cube retroreflectors and cat's eye retroreflectors. Examples of MRR systems using each type are given.

II. Retroreflector Types

Retroreflectors can be divided into two basic classes: those without focusing optics, and those with. The most common non-focusing retroreflector is the corner cube retroreflector (CCR). Focusing retroreflectors are often referred to as "cat's eye" retroreflectors (CERR). These come in several forms, combining lenses and/or mirrors and incorporating an optical focus. Several variations of CERRs have been described in [4].

Several micro-electro-mechanical systems (MEMS) or micromachined approaches to integrating retroreflectors and modulators have shown promise. There are also a variety of retroreflective tapes, paint, and sheets intended primarily for safety. All of these types may prove useful for extremely small devices at short distances, but are generally not optically capable of the long distances achievable with bulk optic retroreflectors.

There is no one type of retroreflector ideal for all MRR systems. Each variation has unique characteristics which may be beneficial or disqualifying in different situations. The retroreflector must be chosen based on the specific system for which it is intended.

Retroreflector choice can not be made without consideration of the modulator type. The retroreflector design must lend itself to integration with the modulator. Because modulators with large areas are used in both CCR- and CERR-based MRRs, most use surface-normal modulators processed on semiconductor wafers. This forces the MRR to accommodate a flat modulator in its optical design. Attempts have been made at using epitaxial liftoff of semiconductor modulators to mate a modulator to a curved CCR, but no practical device has been demonstrated.

A. *Corner cube retroreflectors (CCR)*

CCRs are the most common type of retroreflector in MRRs. Their size, weight, and wide availability make them attractive. Being single, non-focusing elements eliminates alignment concerns, giving consistent, stable performance.

Transmissive modulators are placed directly in front of the CCR. Reflective modulators can be used either as mirrors directing the interrogator beam onto a CCR [5, 6] or as reflective surfaces of the CCR itself [7]. The former reflective solution, however, adds size and weight; the latter requires high precision packaging. Reflective modulators based on semiconductor wafers also suffer from poorer optical performance, as the unavoidable bowing of wafers introduces a focusing element when used in reflection. The effect of wafer bowing is more pronounced in reflective CCR MRRs than in any other type of MRR.

Field of view (FOV) of a CCR is determined by the index of refraction. A BK7 CCR has a 3 dB FOV of approximately ±15°. Higher index materials give larger FOVs; however, they are expensive and difficult to obtain. Most of the higher index materials have lower transmission than more standard glasses, so tradeoffs must be made. Path length through the retro material is proportional to diameter, so materials with lower transmissions may be more tolerable in small CCRs than in larger ones.

The primary disadvantage of CCRs is that the modulator must be as large as the CCR aperture. As range is increased, larger apertures are required, so larger modulators are required. MQW modulators in particular are *RC* time limited, so larger modulators are slower.

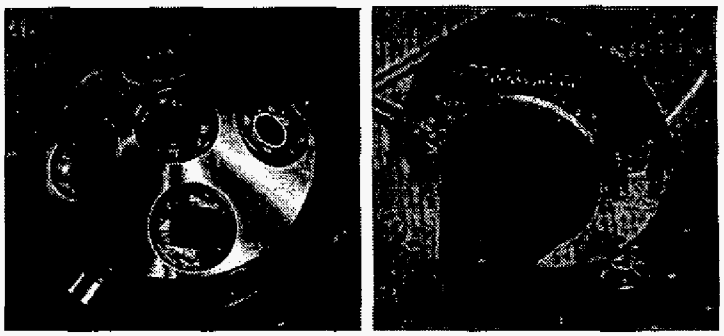

Figure 2: a) Corner cube MRR array b) Aspheric cat's eye MRR

B. Cat's eye retroreflectors (CERR)

CERRS come in many forms, all containing a mirrored surface (not necessarily a plane) onto which light is focused. This enables CERR MRRs to have large optical apertures with small (and thus fast) modulators [8]. This benefit comes at a cost: the location of the focal point on the mirror depends on the angle of incidence. In order to cover a large FOV, the focal surface must be covered with an array of modulators. Maximum benefit is gained from CERRs if the modulator array can react to the angle of the incoming light, switching off unilluminated pixels. This decreases both power consumption and self-heating [9], but requires more complex circuitry than for a CCR MRR.

A benefit of the angle dependence of the focal point location is that it allows the MRR to simultaneously act as a transmitter and as an angle-of-arrival sensor. This same dependence was used to allow angle division multiplexing for multiple independent point to point links from a single telecentric CERR MRR [10]. Flat reflector CERRs benefit from improved passive heat sinking compared to curved reflector CERR designs; they also allow the use of reflective modulators.

The disadvantages of CERRs include larger size and higher cost. Focusing requires precise alignment, thus they are potentially less rugged. Although many CERRs have large FOVs, most designs suited to flat modulators have smaller FOVs than CCRs.

III. General Guidelines

CCRs are best for highly assymetrical links, where small size, light weight, or ruggedness are critical. These attributes also allow a large FOV to be created by arraying. The Naval Research Laboratory's most common MRR is a transmissive MQW modulator coupled to a 6.3 mm CCR. This device has been demonstrated with links up to 5 Mb/s at 1.6 km [11], yet the entire package containing modulator, CCR, mount, window, and drive electronics weighs only 8.5 g (0.3 oz.). This same device has been used in a quincuncial array, increasing the FOV to 60 degrees. The array is shown in Figure 2(a) and weighs 85.5g including all drive electronics. Such arrays have been used in links to a UAV [1] as well as to a boat moving at 15 knots.

CERRs are best for links requiring high data rates at long distance, but with less restriction on space, weight, and power. An aspheric curved focal plane CERR MRR weighing 410 g (including electronics) was used in a 4 km link at 10 Mb/s, and a new modulator has demonstrated 70 Mb/s operation [9]. It is being used in the flat focal plane CERR in Figure 2(b) because the flat focal plane aids heatsinking, which is helpful at high data rates.

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