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IN-AXIS RECEPTION BY POLARIZATION DISCRIMINATION IN A MODULATING-RETROREFLECTOR-BASED FREE-SPACE OPTICAL COMMUNICATION LINK

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ABSTRACT: *A new optical configuration is proposed for ground stations designed to receive information from modulating retroreflector based terminals in a free space optical communication link. This configuration is based on the polarization discrimination of the ground station laser sent to the remote terminal. It achieves the optimal usage of the laser power, which is a key parameter in modulating retroreflector based links. A simulation has been made in order to model the system in terms of power losses and states of polarization and an experimental setup has been implemented to verify the validity of the simulation. A gain of over 6 dB has been measured using the new setup compared with a simple trajectory discrimination setup, achieving a very good agreement with the prediction.*

Key words: *free space optical communications; polarization; retroreflector; retromodulator*

An optical communication link based on a modulating retroreflector (MRR) scheme results in an optical axis that is the same for the transmitted and the received laser beam assuming that the beam width is always larger than the retroreflector aperture [1]; otherwise the returning laser would have an unknown offset from the interrogator optical axis, as it would depend on which of the three retroreflector mirror faces the beam passes first.

The simplest solution to enable the reception of the laser on its way back is to shift the ground receiver out of the optical axis. Because of its simplicity, this has been the traditional configuration in MRR link implementations [2]. However, an important part of the returning light is lost this way, as the center of the gaussian power distribution would fall on the interrogating laser axis, not on the receiver's optical axis. This becomes a limiting drawback as the laser power imposes the boundary in a MRR link. Besides, this configuration can only be used in long distance links, as it is based on the assumption that the laser beam diverges enough to illuminate the whole retroreflector on the one hand and the receiver optics on the other hand, which can be only achieved with a wide beam, as both optical axes differ (Fig. 1).

Another drawback of the configuration described before is that it forces to duplicate the optical segment, one for transmission and another one for reception [3]. Using the same optics for transmitting and receiving is not new in a free space optical communication system. It has been widely addressed in the past by a wavelength discrimination: transmitting by using a given wavelength and receiving using a different one, taking advantage of spectral beamsplitters [4]. Such an optical component cannot be used as there is only one laser with a given wavelength in a MRR link.

The solution proposed in this article is the creation of two different optical paths within the same physical path. The simplest way to receive the returning laser signal in the same physical path is implementing a trajectory discrimination setup by means of a 50/50 beam splitter to deflect the laser on its way

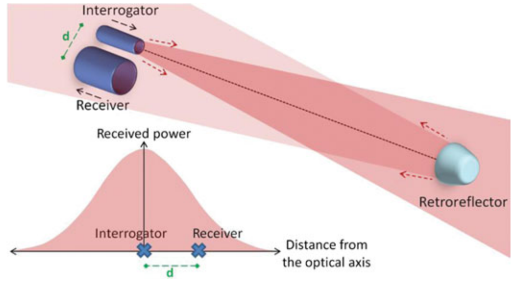

Figure 1 Traditional MRR link setup. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

back towards a photodetector. However, this method has an important drawback, as 50% of the optical power is lost in each pass through the beam splitter.

The proposed technique makes it possible to minimize power losses by transmitting in a linear polarization and receiving in the orthogonal polarization. This can be accomplished with a setup (Fig. 2) consisting of a Faraday rotator as 45° linear polarization is rotated in each of the two passes and a polarized beam splitter (PBS) which deflects the beam to a 90 degrees direction when aligned with the orthogonal polarization. Using this configuration, the range of MRR based links can be extended because it makes it possible to keep the communication in short distances, unlike the traditional technique which needs a minimum divergence due to a long propagation, while achieving longer distances for a given laser power and receiver sensitivity as the traditional losses do not apply here, making the most of the initial power.

In the following simulation, Mueller formulation has been used in order to describe any state of polarization (SOP) with Stokes parameters [5]. The Mueller matrix of a Faraday rotator is the same as the Mueller matrix of a 45° polarization rotator, given in the Eq. (1) [6]. In the Eq. (2), the Mueller matrix of a retroreflector is shown Ref. 7. The equivalent system of the elements in Eq. (1) and (2) is the one given in Eq. (3), designated here as Faraday retroreflector (FarRet).

$$\mathrm{FarRot} = \mathrm{PolRot}(\alpha = 45^\circ) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\cdot\alpha) & \mathrm{sen}(2\cdot\alpha) & 0 \\ 0 & \mathrm{sen}(2\cdot\alpha) & \cos(2\cdot\alpha) & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(90) & \mathrm{sen}(90) & 0 \\ 0 & \mathrm{sen}(90) & \cos(90) & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

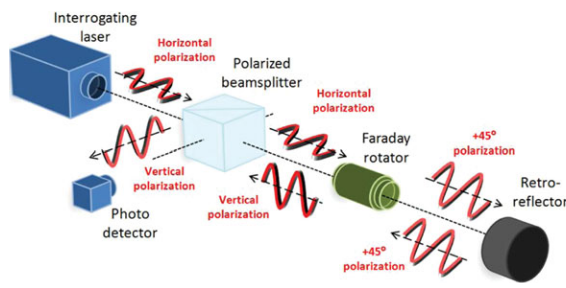

Figure 2 Polarization discrimination setup. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

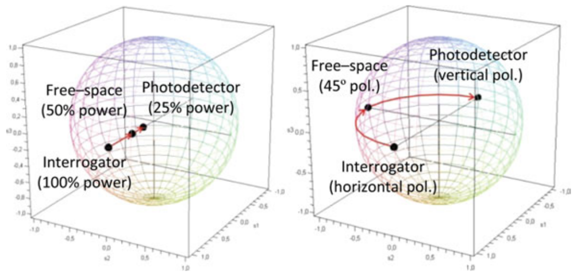

Figure 3 Poincaré sphere showing the transmitted and received SOP with trajectory discrimination setup (left) and polarization discrimination setup (right). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

$$\mathrm{RetRef} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\mathrm{FarRet} = \mathrm{PolRot}(\ \pi/4) \cdot \mathrm{RetRef} \cdot \mathrm{FarRot}(\pi/4) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The Mueller model of the proposed setup (including the retroreflector), when placed as in Figure 2, is the one in the Eq. (4), assuming that the output of the system is directly oriented toward the photodetector input, and the initial polarization is horizontal. This polarization could be any other linear polarization, just changing the PBS alignment, so that the laser light goes through the PBS in the first time without any losses and deflects completely on the way back toward the photodetector, with maximum losses toward the laser following the optical axis.

$$\mathrm{Output} = \mathrm{PBS} \cdot \mathrm{FarRet} \cdot \mathrm{HorLight} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} = \mathrm{VerLight} \quad (4)$$

Figure 3 shows the representation in terms of Poincaré sphere of the changes in polarization and intensity experimented by the laser beam throughout the link (both ways: forward and backward). In the case of 50/50 beamsplitter setup (Fig. 3, left), the final power is reduced by a 0.25 factor, which results in 6 dB losses, when reaching the photodetector at the end of the link. A 50/50 ratio is the most optimal configuration for this setup, compared with any other ratio, which would bring additional losses (e.g., 6.7 dB with a 30/70 beamsplitter or 10.45 dB with a 10/90). As this setup is independent from polarization, if a different one was used, the transition in the Poincaré sphere would be also radial toward the center, starting from the initial SOP in the surface, meaning power losses.

In the case of the new proposed setup (Fig. 3, right), the final effect is equivalent to a 90° linear rotator. If the initial SOP is horizontal, after going through the PBS, the Faraday rotator shifts 45° the linear polarization forward and 45° backward after the retroreflection. Then the PBS deflects the beam 90 degrees toward the photodetector, as the polarization is the orthogonal to the initial one, with no losses in terms of polarization the SOP remains in the Poincaré sphere surface at all times.

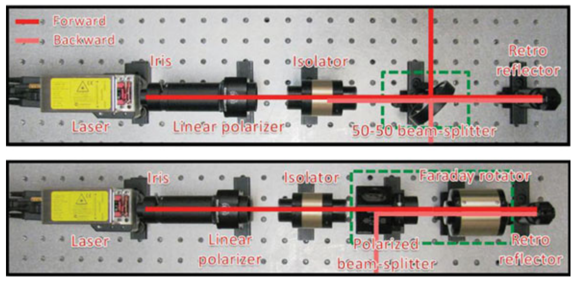

Figure 4 Experimental setups of simple trajectory discrimination (up) and polarization discrimination (down). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

In the Figure 4, two experimental setups are shown: the simple trajectory discrimination setup (Fig. 4, up) and the polarization discrimination setup (Fig. 4, down). A 641 nm laser was used in the experiments, which wavelength determines the coating of the linear polarizer as well as the coating of both beamsplitters in order to achieve the minimum reflectance. The isolator and the Faraday rotator are also wavelength dependant. In both setups, a N BK7 linear polarizer was added after the laser source to impose a >20,000:1 extinction ratio, which is a key feature in order to optimize the performance of the proposed setup, where a pure linear polarization achieves the best results. It is important to note that using a linearly polarized laser, as it was the case in the described setup, the lost power after the N BK7 polarizer, if it is well aligned, is negligible. The isolator was used just for the sake of protection of the laser system to keep it away from any residual light reaching it from the returning beam, essential in the trajectory discrimination setup, but unnecessary in the polarization discrimination setup, as long as the PBS is well aligned with the laser beam. The retroreflector was a 7.16 mm N BK7 corner cube retroreflector and the actual transmittance/reflectance factor of the 50/50 beamsplitter was 50.56/45.73 at 641 nm. One of the values is not so close to 50% due to the lack of coating in one of the sides, which brings 0.2 dB of additional losses that could be avoided with a cube beamsplitter.

The measured results agreed with the simulation and a gain of over 6dB was measured using the proposed setup compared with the 50/50 beam splitter setup. The most significant part of this gain comes from not loosing 50% of the power in each of the passes, which makes up 3 dB+3 dB of gain, and the rest is gained thanks to the use of better coated optics, although an extra improvement would come from using a beam splitter with coatings on both sides of the interface.

Summing up, the validity of the polarization discrimination setup has been simulated, measured, and verified. This configuration has not been used before applied to a MRR link and it can bring important advantages, being the most important one an increment of the gap between the maximum and minimum distance of the communication link. The increment of the distance range is a key feature in applications such as unmanned aerial vehicle (UAV) to ground station lasercom, in which this setup is currently being applied by the authors.

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