Wide-Field-of-View Optical Detectors Using Fused Fiber-Optic Tapers

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Photodetectors used in wireless applications suffer from a trade-off between their response speed and their active area, which limits the received signal-to-noise ratio (SNR). Conventional light-focusing elements used to improve the SNR narrow the field of view (FOV). Herein, we demonstrate a versatile imaging light-focusing element featuring a wide FOV and high optical gain using fused fiber-optic tapers. To verify the practicality of the proposed design, we demonstrated and tested a wide-FOV optical detector for optical wireless communication that can be used for wavelengths ranging from the visible-light band to the near-infrared. The proposed detector offers improvements over luminescent wide-FOV detectors, including higher efficiency, a broader modulation bandwidth, and indefinite stability. © 2021 Optical Society of America

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High-speed photodetectors (PDs) are widely used in various wireless applications, such as optical wireless communication (OWC) networks envisioned to play an important role in fifth-generation (5G) networks and beyond [1, 2]. Collecting high optical power by the PD is a crucial factor to improve the signal-to-noise ratio (SNR) of optical systems. This can be fulfilled by increasing the PD’s active area. However, the larger the active area, the higher the PD’s junction capacitance, and in turn, the resistor-capacitor (RC) time constant. Consequently, there is a trade-off between the PD’s active area and its bandwidth. Therefore, optical receivers commonly consist of a small-active-area PD and a focusing lens. However, the lens limits the field of view (FOV) due to the conservation of étendue [3]. Therefore, designing a high-speed, wide-FOV optical receiver with a relatively large active area has been challenging.

Various solutions have recently been reported to overcome this hurdle. Most prominently, the use of luminescent solar concentrators (LSCs) has shown great potential [4]. These detectors can be designed based on different LSC configurations. A 40-MHz flat LSC coupled to an avalanche photodetector (APD) was shown to have a FOV semiangle of ±60° and an optical gain of one order of magnitude [5]. A similar detector with a nanopatterned LSC exhibited a bandwidth of 100 MHz, an optical gain of 3.2, and a FOV semiangle of 50° [6]. Scintillating fibers have also been used to construct luminescent detectors with an optical gain of up to 12.3 and FOV semiances of 10°–25° [7, 8]. However, due to the long fluorescence lifetime, all aforementioned luminescent detectors have limited modulation bandwidths < 100 MHz, which would be a speed bottleneck in laser-based OWC systems. Moreover, since high-energy photons (375–450 nm) are needed for the excitation of the fluorescent materials, these detectors are not suitable for near-infrared (NIR) free-space optical (FSO) communication based on longer wavelengths (up to 1550 nm) [9]. Moreover, the organic dyes used in such detectors have low conversion efficiency and limited stability over long periods of time.

To fill the research gap in designing wide-FOV imaging detectors while maintaining GHz modulation speeds, we report the use of optical detectors with wide fields of view using fused fiber-optic tapers (FFOTs), which consist of hundreds of thousands of tapered optical fibers. We experimentally demonstrated a high-gain (of more than two orders of magnitude), 1-GHz detector with an overall FOV with acceptance angles of ±30°, corresponding to an effective numerical aperture (NA) of 0.5. The -3-dB modulation bandwidth demonstrated, which is limited by the PD, is at least 10 × broader than that of current state-of-the-art luminescent wide-FOV detectors. This method supports a wide range of the electromagnetic spectrum and does not suffer from the instability and low conversion efficiency associated with organic fluorescent materials. Finally, since the design is based on optical fibers, it can potentially allow for simple integration between free-space and fiber-optic communication.

Figure 1(a) shows the side view of an optical focusing element, whose FOV is indicated by the color gradient. The concept behind the proposed detector is subdividing the area of this optical element, ₐ, into smaller segments, each of which pointing towards a specific direction and corresponding to a range of acceptance angles associated with that direction, as shown in Figs. 1(a)-1(d). In other words, if each segment has a FOV semiangle φ, the nth segment, pointing at an angle ₐ, accepts incident beams with angles within ₐ ± φ. The outputs of these elements share the same area, which increases the focusing ability.

As the number of segments increases, the overlap among the fields of view of neighboring segments increases, as shown in Fig. 1(d). Beams whose incident angles are within the overlapped range can be detected by multiple segments. The overall
area seen by a beam with an angle $\theta_i$ with respect to the vertical in this two-dimensional model can be expressed as:

$$A(\theta_i) = \sum_{\theta_n \in S} \frac{A_0}{N} \cos(\theta_i - \theta_n),$$

where $N$ is the total number of segments and $S$ is the set of all angles corresponding to the segments whose fields of view include $\theta_i$. In other words: $S = \{ \theta_i | \theta_n - \phi < \theta_i < \theta_n + \phi \}$. The amount of power received by the $n^{th}$ segment covered completely by the beam depends on the projected area and is given by:

$$P_n = \frac{A_0}{N} |\mathbf{n}_i \cdot \mathbf{n}_n|,$$

where $E$ is the flux density (irradiance), $\mathbf{n}_i$ is a unit vector in the direction of the beam, and $\mathbf{n}_n$ is a unit vector normal to the $n^{th}$ segment. Since the small segments are facing the angles to which they are assigned, the projected area is improved compared to the flat design in Fig. 1(a).

The proposed design can theoretically be realized in different ways. For example, each segment can be a lens or a compound parabolic concentrator (CPC). However, this impractically costly and complex for a large number of segments. Moreover, the tilt between the PD and each lens or CPC reduces the effective amount of power collected by the PD. Bending a bundle of luminescent fibers to form a spherical surface is another way of realizing a similar design [7]. However, the organic dyes used in these fibers limit the modulation bandwidth, have a low conversion efficiency, have a limited functional lifetime, and require specific wavelengths to be excited. Therefore, we propose the use of fused tapered optical fibers to realize the desired detector (see Supplement 1 for the fabrication details). The large end of each fiber represents a segment pointing at a specific direction and guiding the incoming light to the detector, which can receive multiple modes, in a direction normal to its active area. Unlike CPCs and hemispherical lenses, the proposed design preserves the image at the output, which is necessary for light detection and ranging (LiDAR) and imaging multiple-input and multiple-output (imaging MIMO) communication systems. It is also possible to use it with a multi-pixel detector in angle-diversity detection, in which case each pixel can be smaller and support higher speeds.

Figures 2(a) and 2(b) show regular FFOTs of different sizes. For example, the large FFOT in Fig. 2(a) consists of hundreds of thousands of fibers tapered and fused together into a compact structure. By modifying the design into a FFOT with a convex spherical surface, as shown in Fig. 2(c), consisting of around two hundred thousand tapered fibers, each pointing at a unique direction, we achieved the desired detector with low cost and complexity. In all the tested FFOTs, the cores have a refractive index of 1.72 and their individual diameter at the large end is 80 µm. The core diameter on the small end can be calculated by dividing that of the large end by the square root of the area magnification ratio. The sheath surrounding each fiber has a refractive index of 1.51 and a thickness of 10 µm. The diameter of a single fiber is 100 µm.

Another major advantage of using FFOTs is the ability to modify their FOV based on the application. The convex-surface design described above is suitable for cases in which a wide FOV is required, such as in cases where there is a relative movement between the transmitter and the receiver. In scenarios where the transmitter and receiver are fixed, misalignment can occur due to the channel conditions, including atmospheric or underwater turbulence [9, 10]. In that case, since the photons arrive at the detector at random angles with respect to the propagation axis, a FFOT with a concave surface and fibers pointing inwards [Fig. 2(e)], could be more suitable. Finally, joining or splicing the output port of the FFOT with a specialty multi-mode fiber can potentially form an integrated detector with high immunity to misalignment. This would simplify the convergence of free-space and fiber-optic communication networks.

We experimentally tested the performance of the FFOTs shown in Figs. 2(a)-(c). The active area of the PD has to be as close as possible to the output of the FFOT to achieve the best performance, as shown in Fig. 3(a). We first tested the performance of the FFOTs using a 520-nm narrow laser beam (∼4 mm across). Figure 3(b) shows the normalized received power versus the translation distance from the center of the taper. If we consider a -3-dB cutoff, using the big and small flat FFOTs, the PD can detect the light over a radius of 25 and 4.5 mm, respectively. This can be extended assuming circular symmetry to calculate detection areas of around 19.6 and 0.6 cm², respectively. For the modified FFOT with the convex surface, the radius of detection is 17 mm, corresponding to an area of 9.1 cm² at $\theta = 0°$.

Figure 3(c) shows the normalized received power at different angles. Before tapering, each optical fiber has a NA of 0.8, but
it is reduced by the square root of the area magnification ratio of each FFOT, making the measured -3-dB FOV semioangle of the flat FFOTs around 3°, which is close to that of a typical lens. However, because each individual fiber in the convex-surface FFOT faces a different direction, its -3-dB FOV semioangle is much wider at around 30° (with an effective NA of 0.5).

To test the communication performance using a PD with a small active area to increase the bandwidth of the link, we placed the large end of the 11-mm FFOT as close as possible to the small end (7-mm diameter) of the convex-surface FFOT, forming a single detector whose circular output has a radius of 3.5/11 = 0.32 mm with a total area magnification factor of around 5750. We then placed the output of this detector as close as possible to a 1-GHz APD with a circular active area whose radius is 0.25 mm. While, ideally, the output area of the FFOT should match the PD’s active area, the high performance of the detector allows for a slight mismatch (see Supplement 1 for details on the PD’s size). The normalized frequency response of the link is shown in Fig. 4(a) with and without the FFOTs. No significant effect on the -3-dB bandwidth was observed by adding the two FFOTs, proving that they do not limit the modulation bandwidth of the link. The -3-dB bandwidth is around 1 GHz, which is only limited by the APD. This bandwidth is significantly broader than that of fluorescence-based detectors, whose bandwidth does not exceed 0.1 GHz [5–7]. The frequency response in Fig. 5 in Supplement 1 shows the advantage of using the FFOTs.

We also tested the transmission efficiency, $\eta(\lambda)$, of the two FFOTs, defined as the ratio of the output optical power to the input optical power, where $\lambda$ is the wavelength of the incident light in free space. Figure 4(b) shows the transmission efficiency at different wavelengths. The efficiency values range from 55.0% to 70.7%, which is much higher than the 1.5% conversion efficiency reported for some of the fluorescence-based detectors [7], even when the two FFOTs are combined. Moreover, this high efficiency is maintained for a wide range of wavelengths, even as long as 1550 nm, which is not the case for fluorescence-based detectors that require shorter wavelengths for excitation. It is, therefore, possible to use FFOT detectors in a variety of applications that rely on different wavelengths, such as in FSO communication and in integrating OWC networks with NIR fiber-optic networks.

The optical power gain, $G(\theta, \lambda)$, of the detector over a bare PD with an active area, $A_{PD}$, matching that of the output of the combined FFOTs can be estimated by:

$$G(\theta, \lambda) = \frac{A(\theta)}{A_{PD} \cos(\theta)} \eta(\lambda).$$

In other words, the gain is equal to the product of the area magnification ratio, $M(\theta)$, and the efficiency. The high value of the magnification ratio more than compensates for the losses from the transmission efficiencies of the combined FFOTs, providing higher input power to the PD. For example, at 642 nm, an optical gain of more than two orders of magnitude (~121.3) was measured for the combined FFOTs at $\theta = 0$. This overall gain is therefore significantly higher than that of luminescent detectors (3.2 [6], 12 [5], and 12.3 [7] optical gains). As a reference, a CPC with a similar -3-dB FOV semioangle has a 4.5 optical gain [11]. The dependence of $M(\theta)$ on the angle is due to differences in the effective area for different angles of incidence that might arise from imperfections in the arrangement of the fibers in the convex-surface FFOT. However, for a perfectly spherical arrangement, the projected area seen by any wide collimated beam should be the same for all angles. In our tests at 642 nm, for a divergent beam emulating long-distance transmission, an optical gain around one order of magnitude is maintained at the maximum detection angle. The optical gain can be higher for more collimated beams and can be improved further using the methods detailed below.

As a proof-of-concept demonstration, we established an OWC link based on a 642-nm laser, selected based on the transmission efficiency of the FFOTs and the responsivity of the APD (35 A/W). We measured the bit error ratio (BER) of the received signal at a data rate of 1 Gbit/s using on-off keying (OOK) at different angles and translations, as shown in Figs. 5(a) and 5(b), respectively. The x-axes in both figures were normalized for symmetry. For angles between $-32.5^\circ$ and $32.5^\circ$ and
The BER at different (a) angles and (b) translations with a data rate of 1 Gbit/s. (c) The BER at different data rates.

translations between −1.75 cm and 1.75 cm, the BER measured was below the 7%-overhead forward error correction (FEC) BER limit (3.8 × 10^{-3}). This is verified by calculating the normalized optical power loss from the BER. The optical power is directly proportional to the APD’s current, which is directly proportional to the square root of the SNR. The BER for OOK is given by BER = Q(\sqrt{SNR_o}) \cdot \max \{Q^{-1}\{BER(d, \theta_i)\} \}. The normalized loss in Figs. 5(a) and 5(b) is defined as −10 log\{P_R(d, \theta_i)\}. The normalized loss is below 3 dB for the tested angles and translations. Figure 5(c) shows the BER at \theta_i = 0 for different data rates. Using other spectrally efficient modulation schemes can potentially offer significantly faster links.

While this is a proof-of-concept example, other applications can benefit from the demonstrated detector, such as integrating FSO communication links with fiber-optic networks by fusing the output of the FFOT with a fiber-optic cable. Moreover, several modifications can be made to improve the communication performance. For example, while designing FFOTs without extra-mural absorption (EMA) can result in a blurry image, it can improve the transmission efficiency [13]. Another method to improve the transmission efficiency is to reduce the reflection from the FFOTs, which, assuming normal incidence on each fiber, can be calculated using R = [(n_g - n) / (n_g + n)]^2, where n_g and n are the refractive indices of the cores and the surrounding medium, respectively. In our tests, the reflection is around 7%. As the light exits the taper, it experiences reflection again. Assuming a small air gap between the taper and the PD, the total reflection loss is approximately 13.5%. By applying an anti-reflection coating, this loss can be minimized [13]. Furthermore, increasing the packing fraction, defined as the ratio of the areas of the cores to the total area of the taper, by reducing the thickness of the sheaths can improve the efficiency. Replacing the two FFOTs used in this work with a single one whose output matches the size of the PD’s active area can eliminate the coupling losses between the two FFOTs. Moreover, by focusing only on the communication performance, FFOTs with a wider FOV that are coupled directly to PDs can offer better performance.

We have demonstrated the practicality of developing an imaging, wide-FOV optical detector based on FFOTs. Though the work presented herein demonstrated a proof-of-concept OWC link, different designs can be easily adapted for other applications. The advantages of FFOTs over fluorescence-based detectors include having no limitation on the modulation bandwidth, offering higher efficiency, indefinite stability, and operating over a wide range of wavelengths. This allows their use in applications that require specific wavelengths, such as FSO communication links. Future design considerations can potentially improve the performance of the wide-FOV detector by enhancing its transmission efficiency. Therefore, our work paves the way for future studies by proposing a new design for imaging, wide-FOV optical detectors used in a wide variety of wireless applications.

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**Disclosures.** The authors declare no conflicts of interest.

See Supplement 1 for supporting content.

**REFERENCES**

FULL REFERENCES


