Enhanced-Field-of-View Solid-State VCSEL Beam Scanner with Lateral Resolution Points of More than 1200

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Abstract *We introduced one-dimensional DOE to a solid-state VCSEL beam scanner for increasing its scanning field-of-view in 3D sensing. It produced covered field-of-view of 36°×16°and a record number of resolution points of more than 1,200 with external light driving and 300 in a tunable VCSEL-integrated scanner.*

Introduction

Beam scanning technology has been attracting much attention because of its extraordinary performance in 3D sensing, such as LiDAR and 3D camera in smart phones. Most of mature beam scanning solutions are based on MEMs technology[1]. Due to movable elements and extra MEMs system, its long-term reliability, component size and cost are still critical issues. Recently, many solid-state beam scanners based on optical phase array[2], photonic crystal[3] and Si-phonics-based array emitter [4] are emerging to meet the demand. However, the challenges of limited covered field-of-view and resolution points have so far precluded their further applications in commercial field. Also, Time-of-Flight (TOF) LiDAR has been a major choice for LiDAR, which needs a high output power.

Previously, our group reported a compact active VCSEL beam scanner with high resolving ability and high-power [5~6], but due to limited scan range of less than 20°, the total number of resolution points is also difficult to reach over 500. Efforts to increase the covered field-of-view will lead to proportional improvement of resolution points. As adopted in projection of diffracted pattern for structured-light sensing [7~8], diffractive optical element (DOE) presents an available path towards our goal because it can split the beam to a wider field. In this paper, we propose and demonstrate our beam scanner equipped with a DOE.

Principle of beam scanner using DOE

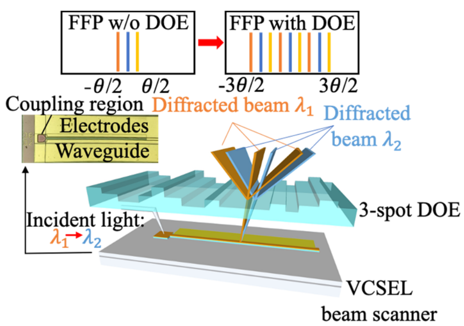

Fig. 1. Principe for enlarging the FOV of beam scanner

Figure 1 illustrates the basic schematic of our beam scanner. It is composed of a VCSEL beam scanner and a DOE that is placed above the beam scanner. The VCSEL beam scanner [5] works as a slow-light waveguide with aperture. If the external light of different wavelengths (e.g. λ_1, λ_2) is coupled into the VCSEL scanner, the output light from the oxide aperture will be deflected to different angle correspondingly and reshaped as a fan beam (Orange and blue). When a 3-spot 1D DOE is placed on the beam scanner, the original beam will be split to 3 fan beams with certain separation. If the scan range of the beam scanner is equal to the separation, the separation between split fan beams will be filled by scanned fan beams. It means the beam scanner could cover a field-of-view 3 times as large as the original scan range.

Experimental results by using beam scanner with external light coupling

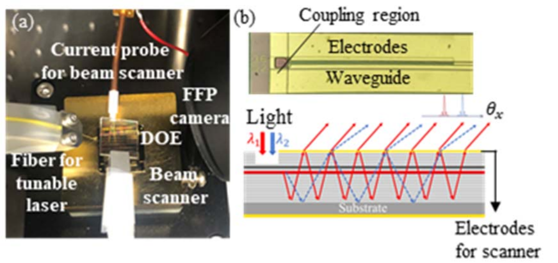

Fig. 2. (a) Photo of measurement setup of beam scanner (External light driving) equipped with a DOE (b) Photo (Top) and structure (Bottom) of VCSEL beam scanner

The experimental setup for measuring the far field pattern (FFP) of our VCSEL beam scanner equipped with a DOE is shown in Fig. 2(a). External light from a tunable laser is coupled into the beam scanner through a lensed fiber. With tuning the wavelength, the output beam will be steered as shown in Fig. 2(b) [5]. The current is injected into the VCSEL scanner through a probe to compensate the loss due to propagation in the scanner. Finally, the output light from the beam scanner will pass through a 3-spot DOE that is

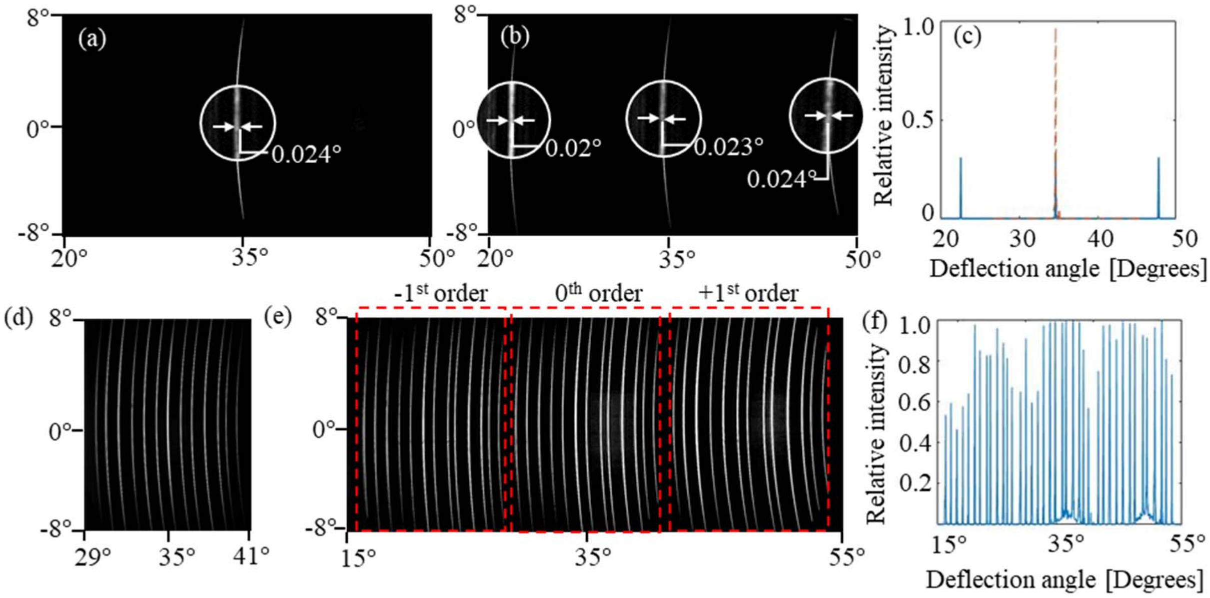

Fig. 3. FFP of static beam from scanner (a) without and (b) with DOE (In circle is FFP captured by high resolution camera); (c)Profile of static beam from scanner with (Solid line) and without (dashed line) DOE; (d) FFP of scanned beam from scanner without DOE (e) FFP of scanned beam from scanner with DOE; (f) Profile of scanned beam from scanner with DOE

placed 1cm above the beam scanner and the spacing can be reduced for making its module size smaller. The FFP image is captured by an FFP camera.

The measurement result is illustrated in Fig. 3 for a 6mm-long scanner. The static characteristic was firstly illustrated in Fig. 3(a)~(c). When 840nm external light is coupled to the beam scanner and current of 500mA is injected to the scanner, a nearly diffraction-limited narrow fan beam can be seen as shown in Fig. 3(a). The output power is typically 3W at current of 5A under pulsed operations. The fan beam was split to 3 fan beams with almost same intensity and separation angle of 13° (between -1st and 0th order) and 14° (between 0th and +1st order) by DOE as shown in Fig. 3(b) and (c). Because the beam divergence is smaller than the resolving ability of FFP camera, we examined the beam divergence of split beam through high-resolution mode of FFP observation system as shown in the circle of Fig. 3(b). It shows the beam divergence is around 0.02° and nearly does not change after adding a DOE. Besides, from Fig. 3(c), it could be seen that the intensity of split beams is almost equally 1/3 of the original beam and no extra beam can be seen in the figure, which indicates that all the input power is divided into 3 beams almost equally.

Then, the beam scanning was carried out through tuning the wavelength of coupled external light ranging from 836.8nm to 844.5nm by 13 steps. It turns out original scan range of about 12° as shown in Fig. 3(d). Being split by DOE, the range that beam covers could be increased to 36°, which is nearly 3 times as large as the original scan range as shown in Fig. 3(e). In this case the total number of resolution points should be equal to the whole covered range divided by the beam divergence. Although it indicates the narrow beam divergence of 0.02° at a fixed wavelength, the actual beam divergence in scanning condition will vary with wavelength tuning from 0.018° to 0.03°. It could be calculated that the maximum number of resolution points be larger than 1200. It is a record number for solid state scanners. It also shows the intensity profile of scanned beam in Fig .3(f). Its intensity variation (*Standard deviation of intensity/average intensity*) is 19%.

Experimental results by using a beam scanner integrated with VCSEL

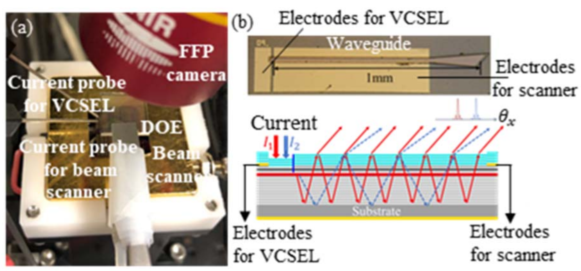

Fig. 4. (a) Photo of measurement setup of beam scanner (integrated with VCSEL) equipped with a DOE (b) Photo (Top) and structure (Bottom) of VCSEL beam scanner

To miniaturize size of the beam scanner for compact application such as 3D cameras in mobile phones, it is useful to integrate an on-chip tunable light source to the beam scanner rather

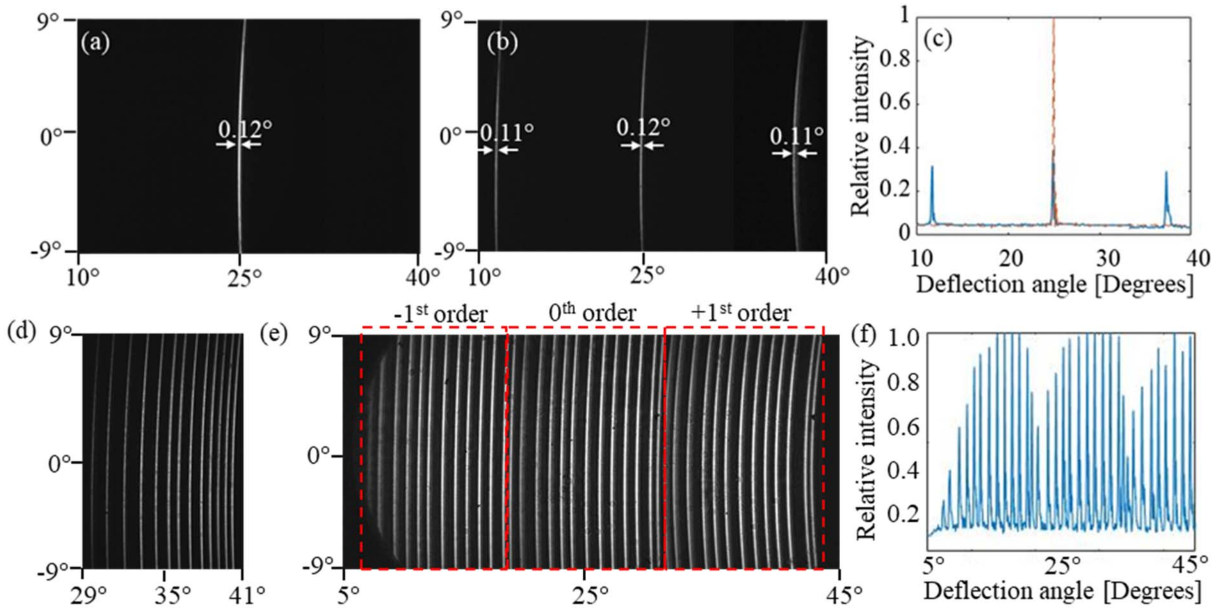

Fig. 5. FFP of static beam from scanner (a) without and (b) with DOE; (c)Profile of static beam from scanner with (Solid line) and without (dashed line) DOE; (d) FFP of scanned beam from scanner without DOE (e) FFP of scanned beam from scanner with DOE; (f) Profile of scanned beam from scanner with DOE

than coupling external light. Such a beam scanner integrated with a tunable VCSEL[6] was reported by our group previously. Its photo and schematic are shown in Fig. 4(b). The length of the integrated scanner is 1 mm. Through varying the current injected into VCSEL its lasing wavelength will also vary thanks to a self-heating effect. Thus, as explained in external-light-driving beam scanner, the deflection angle of output light will steer correspondingly. We also equipped this kind of beam scanner with the same 3-spot DOE to enlarge its covered field. To measure its performance, we established the setup shown in Fig. 4(a). Two probes are set to inject current to VCSEL and beam scanner separately. Output light through DOE that placed 1cm above the beam scanner will be received by FFP camera.

With injecting current of 3mA to VCSEL and 50mA to beam scanner, the static FFP of output beam from beam scanner is shown in Fig. 5(a)~(c). It is almost similar to the previous section, but the deflection angle is smaller than beam scanner with external light due to a limited tuning range of an electro-thermally tunable VCSEL. Thanks to the smaller aperture of this device, the fan angle is increased to 18°. Similarly, by placing a DOE, the original beam was split to 3 lines with similar intensity, of which the separation is 12° as shown in Fig. 5 (b) and (c). The reason why the separation angle is slightly different from that mentioned in this experiment might be the different deflection angle of the beam scanner.

The scanned beams with changing the current injected into VCSEL from 1.5mA to 5mA are illustrated in Fig. 5(d). Without DOE, the beam scanner could also cover a scan field of more than 12 degrees. Passing through the DOE, the beam will be also split as shown in Fig. 5(e). The beam covers a total field-of-view of 18°×36° with a number of the lateral resolution point of 300 because the beam divergence is 0.12°, which could be improved by increasing the length of the beam scanner to several mm. Figure 5(f) shows the intensity uniformity of scanned beams and through calculation we can find that the intensity variation is 26%

Conclusion

We demonstrated solid-state VCSEL beam scanners equipped with DOE in this report. The beam scanner with external light coupling can cover a field-of-view of 36°×16° with a record resolution points of more than 1200. In addition, the ultra-compact beam scanner integrated with VCSEL can cover larger field of 36°×18° with resolution points of more than 300. Thanks to a DOE with larger diffracted angles and more splitter fan beams, the total field-of-view could be increased over 60° and ultrahigh resolution points of more than 2000 could be expected for the proposed solid-state scanners.

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