Compact 1D/2D VCSEL Beam Scanner with Enhanced Field of View and High Resolution

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Abstract *We realized 1D beam steering with field of view of >100° and resolution number of >1400 by using electrical-driven solid-state beam scanner with submodule size of 10mm×6mm×3mm. We also demonstrated 2D-beam steering with field of view of 35°× 15° by integration of beam scanners array.*

Introduction

Nowadays, we are witnessing the blowout of 3D sensing market thanks to its application such as LiDAR in automotive and time-of-flight camera in mobile phones. Being the key element of 3D sensing, beam scanners have been attracting much attention. As a mature technology, beam scanners based on mechanical and MEMS technology has been equipped with current 3D sensors [1], but its inserted dynamic element brings concern about its long-term availability, package size and cost efficiency. Therefore, non-mechanical beam scanning technology, such as optical phase array [2] and modulation of photonic crystal [3] offers the opportunity of next-generation solid-state LiDAR. However, their limited resolution, small field of view and hard integrability with a light source are still challengeable for practical applications.

Previously, we reported a VCSEL-based solitary beam scanner with field of view of >100° and high resolution of >1800 [4] by using a DOE. As mentioned, its requirement of external tunable light source make it difficult to be integrated within small size. Our group recently invented thermally tunable slow-light VCSEL [5] and succeeded in integrating it to the solitary beam scanner [6] to realize electrical-riven 1D beam steering. However, its scan range is smaller than 10° due to the limited thermal tuning efficiency. Besides, its emission angle was far away from a vertical direction, so it is difficult to equip a DOE to enhance the field of view and cover the vertical field. In this paper, we proposed counter-propagation beam scanners with Au-coated prism mirror and DOE. For higher light intensity at a target, we also demonstrated 2D beam scanning by integration of scanners.

1D beam steering by using electrical-driven scanner equipped with DOE and prism mirror

Figure 1 (a) and (b) illustrate the basic schematic of our beam scanner. It is composed of two counter-propagation electrical-driven beam scanners (right- and left- emitting scanners), two prisms with gold being coated on the slope and a 7-spot DOE. The structure of counter-propagation electrical-driven beam scanner was also shown in Fig. 1 (a). Each scanner consists of a slow-light VCSEL with surface grating [5] and a solitary beam scanner [7]. Tuning the current

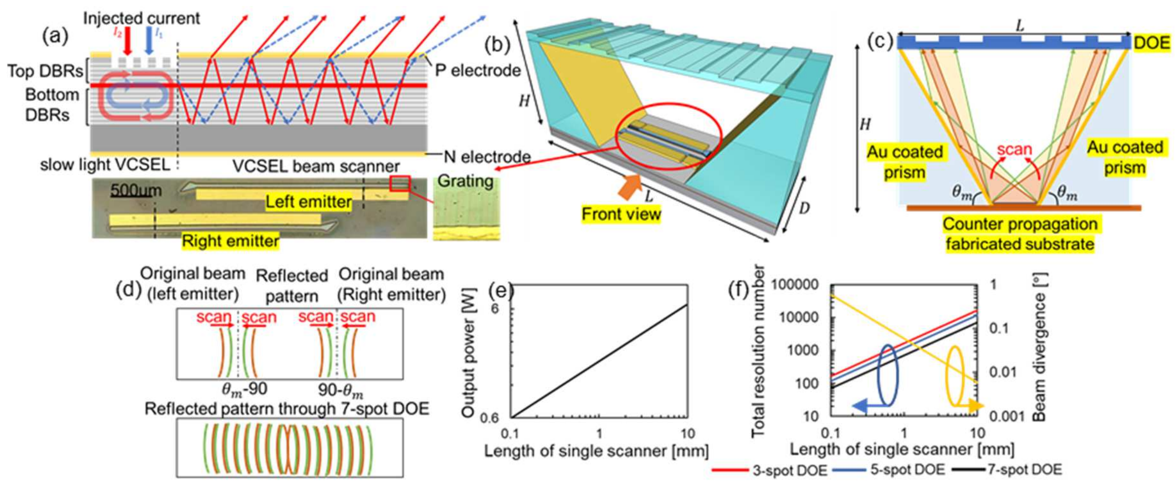

Fig. 1: (a) Schematic of electrical-driven beam scanner; (b) schematic and (c) front-view schematic of beam scanner equipped with DOE and Au-coated prism (d) Beam illustration by using the system (d) Theoretical power of single scanner (f) potential beam divergence and total number of resolution points as function of length of single scanner

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injected into the slow-light VCSEL, slow light with tunable wavelength will be coupled into the solitary VCSEL scanner. Thanks to the large angular dispersion, the scanner will finally emit diffraction-limited fan beam of continuous deflection angle with varying the current injected into the slow-light VCSEL (I_{laser}). Then, as Fig. 1(b) and (c) show, the beam emitted from scanners will be reflected by the prism mirror and split to 7 beams with similar separation of 7° by the DOE. 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 7 times as large as the original scan range. If counter-propagation scanners are applied, the field of view as well as resolution number could be double.

The size of prism and DOE should be designed to capture all light emitted from scanners. For 2mm-long scanners, the minimum submodule length L, height H and width D are 10mm, 6mm and 3mm, respectively. As Figs. 1 (e) and (f) show, the power and resolution number are positively related to the scanner length. For the applications without requirement of extremely high power and high resolution, the scanner length could be reduced to less than 1mm. Thus, the submodule size could be optimized to <3mm×2mm×1mm and meet the requirement of applications on mobile devices.

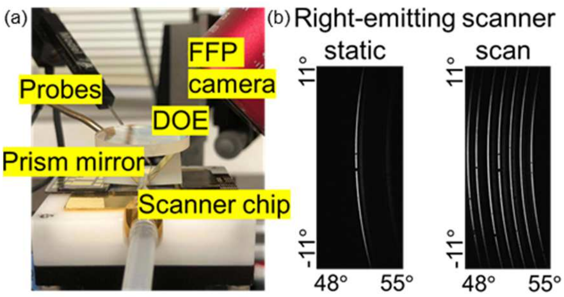

Fig. 2: (a) Photo of measurement system; (b) Original FFP beam of right-emitting scanner

The photo of the measurement system is shown in Fig. 2 (a). Two prism mirrors are placed directly on the scanner chip and a DOE is supported by the mirrors. Without prism mirror and DOE, the static far-field pattern (FFP) beam of right-emitting scanners was measured when the I_{laser} is 190mA as shown in Figs. 2 (b). Varying I_{laser} from 40mA to 270mA, the scanned beams were also measured. Also, the left-emitting scanner shows symmetrical FFP when the I_{laser} is varied from 40mA to 267mA. They could both scan for 7°. The average beam divergence is 0.65° and 0.72°, which indicates the resolution number of 107 and 97, respectively. The beam divergence is larger than the calculated result shown in Fig. 1 (f) due to fabrication process problems. We have obtained the nearly-diffraction-limited beam divergence and high single-mode power of >3W by better fabrication process [8].

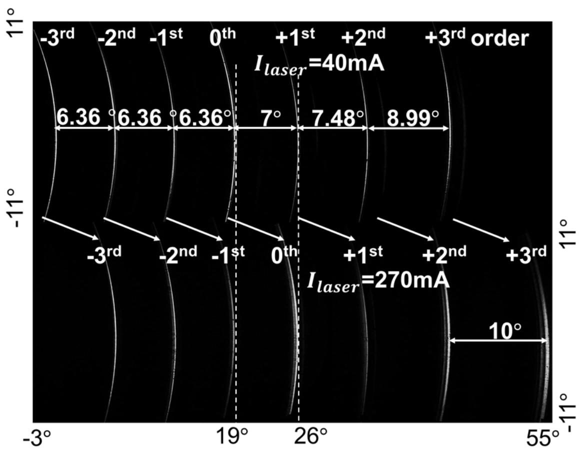

Fig. 3: Static FFP of right-emitting scanner

Then, we measured the static FFP of right-emitting scanner as shown in Fig. 3. The original scan range of 48°~55° is mirrored to 19°~26° as 0th order. We firstly measured the FFP when I_{laser} begins at 40mA. It could be seen that the original single beam was split to 7 beams with certain separation. The difference of separation comes from the non-normal incident to DOE. However, when we scan for 7° to fulfil the separation of 0th and 1st order, the separation between each neighbouring orders will be automatically fulfilled. It could be confirmed by scanning I_{laser} from 40mA to 270mA as shown in Fig. 3. It also shows the field of view could be increased to >55°. For left-emitting scanner, the symmetric steering behaviour could be observed.

We also demonstrated continuous beam

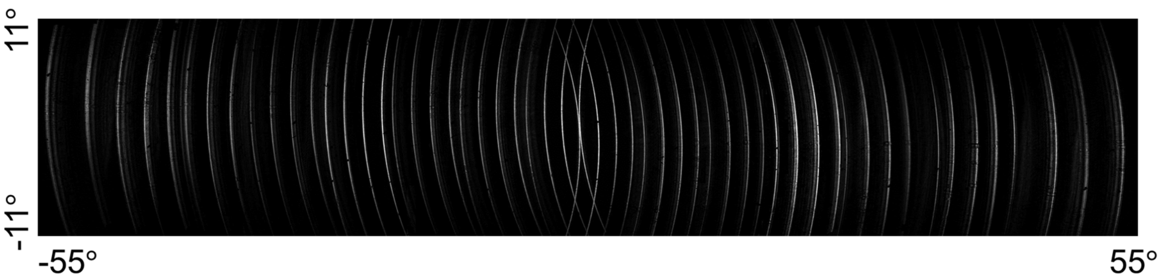

Fig. 4: Scanned FFP of counter-propagation beam scanner with DOE and prism mirrors

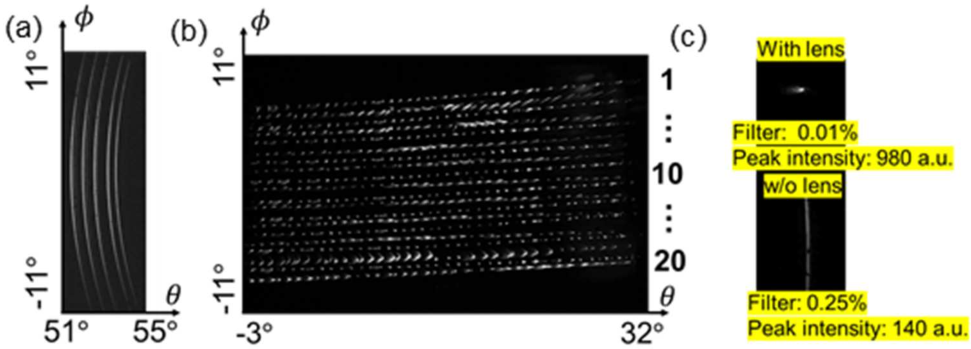

Fig. 5: (a) Original scanned beam of single scanner in the array and (b) 2D beam steering FFP (c) Comparison of intensity of collimated spot and uncollimated fan beam

scanning as shown in Fig. 4. It could cover a total field of view of 110° × 22°. It indicates that the total number of resolution points for this counter-propagation beam scanners should be 1428. The intensity variation in the entire scan range is 22% and 25% for right- and left-emitting scanners, respectively.

2D beam scanning by equipping prism mirror, DOE and cylindrical lens to electrical-driven beam scanners array

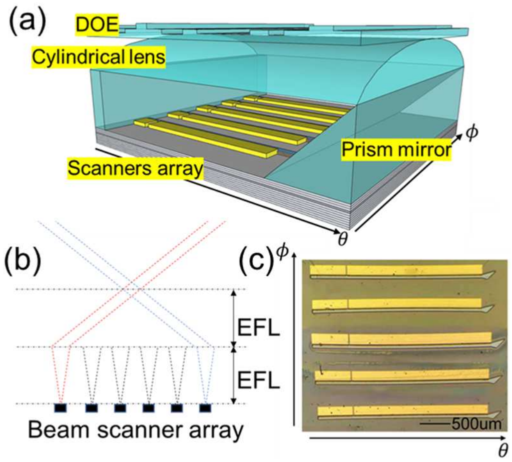

Fig. 6: (a) The schematic of 2D beam scanning (b) Side view illustration (c) Photo of scanners array

Figure 6 (a) shows the schematic of 2D beam scanning. Electrical-driven beam scanners were integrated on the same chip to form an array with pitch size of 500um. The prism is placed to guide the deflection angle and a cylindrical lens is used to focus the fan beam. Depending on the relative position of scanners and the lens, the propagation direction could be also changed as shown in Fig. 6 (b). Therefore, it forms scanning in ϕ direction by electrically switching the different scanners. A DOE is placed finally to expand the field of view in θ direction.

In the experiment, we fabricated 5-scanner array as Fig. 6 (c) shows and use a cylindrical lens with effective focal length (EFL) of 15mm. Because the original scan range is smaller than the previous counter-propagation scanners, we chose a 10-spot DOE with smaller separation of 3.5°. The 1D beam scanning FFP of single scanner were measured as shown in Figs. 5 (a). Then we placed the cylindrical lens and DOE to achieved 2D beam steering by varying current injected into a slow-light VCSEL from 73 mA to 215 mA and switching the 5 scanners one by one as shown in Fig. 5 (b) No. 8, 10, 12, 14, 16. To further demonstrate the potential of 2D beam scanning, we formed 15 virtual scanners by moving the cylindrical lens in ϕ direction and obtained the scanned FFP as other No. shown in Fig. 5 (b). It covers the field of view of 35°× 15°. The average beam divergence in θ direction is 0.15°, which indicates the resolution number of 233 × 20. It could be improved by better fabrication process and extending the scanner length. It is also easy to get double field of view and resolution number by integrating a counter-propagation scanner. In addition, the collimated beam intensity was largely improved to 175 times as large as an uncollimated fan beam shown in Fig. 5 (c), which is greatly helpful for long-distance LiDAR.

Conclusions

We proposed counter-propagation electrical-driven beam scanners to realize 1D beam scanning with ultra-large field of view of 110° × 22° and high resolution of 1428. It shows potential higher resolution by better fabrication process and possible extremely small submodule size of <3mm×2mm×1mm. Besides, 2D beam steering of 35°× 15° was achieved by integration of scanners array. Its great intensity improvement gives more possibility for long-range 3D sensing. The field of view and resolution numbers could be further increased by integrating more scanners and using cylindrical lens with smaller EFL.

Acknowledgements

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