Regional Pulselength and Delay Nonuniformity of Modulated 940 nm Vertical-Cavity Surface-Emitting Laser Array

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Under pulsed modulation, the emission uniformity in terms of pulselength and delay of a 940 nm multimode vertical-cavity surface-emitting laser (MM-VCSEL) array is characterized by analyzing the position-dependent pulsating and chirping dynamics among localized 600 VCSEL elements. In addition, the MM-VCSEL array biased nearly threshold current (Ith) of 350 mA with a low resistance of 0.72 Ω reveals serious impedance mismatching with a high reflection coefficient (Γ') of −0.97. The MM-VCSEL array biased below threshold (at Iac ≈ 0.9 Ith) reveals low-impedance and high-capacitance behavior to result in large modulation reflection with allowable −3 dB bandwidth of 0.8 GHz. The nonuniform optical intensity and delay distribution among all MM-VCSEL elements corroborate that the gradually enlarged inductance attenuates the modulation current away from bond wires. By modulating the 0.9Ith-biased MM-VCSEL array with an 127 ps-wide electrical pulse with a peak amplitude of 15.3 V, a multimode fiber probe collects the single MM-VCSEL output with average power, peak voltage, and pulselength of 0.08 mW, 25.1 mV, and 602 ps. The delay time as large as 273.4 ps between the nearest and farthest parts of local MM-VCSEL elements in the array determines its impulse response and uniformity for applications.

1. Introduction

The vertical-cavity surface-emitting laser (VCSEL) array has rapidly emerged as a key visual device to meet the future demands on 3D distant sensing, morphological profiling, autonomous driving, augmented reality gaming, and intelligent networking applications. With the success of the single-chip VCSELs which play an important role in short-distance intradata center communication,[1] the mature fabrication technology benefits the VCSEL from advantages of lower power consumption and higher modulation speed at a lower cost, which has pushed forward the popular research fields of the VCSELs extended from the transmitter to sensors, light detection and ranging (LiDAR), scanners, etc. in recent years. At the current stage, the most intriguing technique is the 3D sensing for LiDAR application,[2-3] which categorizes the objective recognition modes using either structured lighting (SL) or the time-of-flighting (ToF) detection. In contrast to the SL technique which projects the beam spot into the million point patterns via microoptical elements for reconstructing the object with an image processing algorithm,[4] the ToF simply utilizes the optical pulse to scan the object and measure the round-trip traveling time between emitted and reflected pulses for mapping the surface contour of the object.[5] Especially, the precise driving of the addressable elements in rows and columns of the 2D VCSEL array can further improve the contour resolution during morphic recognition with selective portion of illumination and field of view. Traditionally, the direct approach to effectively increase the output power of a single VCSEL element can be implemented by enlarging its aperture diameter, but the transverse mode number concurrently increases to fluctuate the far-field emission pattern with changing current and temperature. To achieve a Gaussian-like far-field distribution with approximately uniform current and light distribution in a 2D large-aperture VCSEL array, the optimized design on the period of the aligned chip is rigorous as it simultaneously affects the contact inductance and field flatness. This results in the far field of the VCSEL array approaching a very similar distribution with summed element power as compared with a single VCSEL chip. In contrast, the optical pulsation

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of the VCSEL can be easily performed using the pulsed modulation technique, which is often used in other kinds of semiconductors or fiber lasers,\(^6\)–\(^8\) and the fine depth resolution of ToF strictly relies on the sufficiently smaller pulsewidth for shorter flight-time identification, which leads to a trade-off on designing the chip size and number in the VCSEL array as the higher peak power of the pulse is crucial for the longer sensing distance. Regarding this issue, few discussions in previous works were paid and emphasized on characterizing the broadened optical pulsation and the lengthened delay time among the optical pulses contributed by adjacent elements in the VCSEL array. For the 3D sensing application, the light source with high throughput stability and short switching response is very important to improve both the distance of detection and the resolution of identification. Even though most previous works only discussed the pulsed modulation of a single VCSEL,\(^9\)–\(^11\) few works on the pulsed modulation performance were reported for the VCSEL array. Therefore, the 2D VCSEL array integrated with such a large amount of 621 VCSEL elements in pulsed mode is preliminarily investigated for future sensing or mapping applications. In particular, almost no work is focused on studying the distribution uniformity of the pulsed modulation response in different local areas of the VCSEL array. This work emphasizes characterizing the pulsewidth and relative delay of the generated pulses from local areas of the VCSEL array. This helps to understand the effect of electrical pulse propagation along the electrodes of the VCSEL array on the optical pulse generated near or far from the electrode.

In this work, a 940 nm commercially available multimode (MM) VCSEL array adhered on a ceramic submount with a gold-plated coplanar stripeline contact electrode is used for pulsed pulsation to meet the demand of ToF sensing application. With parallel Au wire bonding, the top p-type, and silver glue coating the bottom n-type electrodes of the MM-VCSEL array to the signal and ground transmission line patterns, the basic lasing performance is analyzed via the linear and differential power-to-current (\(P\rightarrow I\) and \(dP_{\text{out}}/dI_{\text{bias}}\)) and voltage-to-current (\(V\rightarrow I\) and \(dV/dI\)) responses. The vector scattering parametric analysis is performed for small-signal bandwidth and an equivalent circuit model. In particular, the evolution of the bias-dependent dynamic chirp behavior of the MM-VCSEL array is analyzed to understand its electro-to-optical pulsating characteristics in detail. The laser beam profiler is used to scan the light-emitting area for exploring the current distribution uniformity of the MM-VCSEL array. Finally, the pulsed modulation scheme adopted for short-pulse and high-power pulsation is optimized to realize the localized pulsewidth broadening and relative time delay among four corners of the MM-VCSEL array, which figures out the extreme performance of the pulsed MM-VCSEL for future ToF sensing applications.

2. Experimental Section

Figure 1a exhibits the top-view microscopic image of the MM-VCSEL array connected to the ground signal (GS) submount with eight Au bonding wires, and Figure 1b illustrates the 2D cross-sectional-view structure of the single MM-VCSEL with its aperture size of 7.5 μm confined by the bilayer-oxide mesa.

Figure 1. Experimental setup of delay time measurement for different positions of the MM-VCSEL array. a) The eight-bonding MM-VCSEL array chip on the microscope and b) 2D schematic configuration of each MM-VCSEL unit of bilayer oxide-confined aperture. c) Experimental setup of delay time measurement for different positions of the MM-VCSEL array.
The VCSEL array contained 621 (23 × 27) single MM-VCSEL elements. In the bottom, the cavity mirror with n-type distributed Bragg reflector (DBR) structure was epitaxial on a GaAs substrate, which was constructed by eight pairs of the n-type Al0.9Ga0.1 As/Al0.12Ga0.88 As layers staggered with 25 pairs of the undoped AlAs/Al0.1Ga0.9 As layers. Upon the n-DBR, the active layer was constructed with a set of the InxGa(1-x)As multi-quantum wells (MQWs) sandwiched by corresponding barrier layers. By increasing the MQW number, the higher optical gain and lasing power of a single MM-VCSEL element were achieved at a cost of the larger threshold current and smaller modulation bandwidth. An epitaxial five-pair In0.072Ga0.928 As MQM structure was used as the active layer in the single MM-VCSEL element. In the typical design, a single VCSEL element configured with five pairs of the InGaAs MQW structure possessed a low threshold current, sufficient optical gain, and high modulation bandwidth. However, the VCSEL array was composed of several hundred parallel-connected VCSEL elements, which effectively caused the larger threshold current and the smaller modulation bandwidth. Therefore, the compromization between threshold current and modulation bandwidth of the VCSEL array relied strictly on choosing the appropriate quantity of the VCSEL elements rather than adjusting the pair number of the InGaAs MQW epitaxial layer. Up the active layer, another two pairs of the doped Al0.93Ga0.07 As/Al0.12Ga0.88 As layers followed by four pairs of the doped Al0.96Ga0.04 As/Al0.12Ga0.88 As layers were used to further facilitate the current injection and reduce the parasitic capacitance of the single MM-VCSEL element. Finally, a p-type DBR configured with 14 pairs of the Al0.96Ga0.04 As/Al0.12Ga0.88 As layers with high dopants was used as the top mirror to form a highly reflective resonant cavity, which concurrently enhanced the current injection and reduced resistive heating as compared to traditional DBR with high resistance. The uni- and biparabolic doping schemes were individually performed in the corresponding structures, respectively, which located at standing-wave maximum and null to further reduce the optical loss for achieving the highly efficient lasing performance. In particular, a continuously gradient molar ratio design was used to suppress the interfacial bandgap discontinuity among the heterostructural interfaces of the DBR pairs, which allowed the electron—hole pair to flexibly flow through the whole DBR layers without suffering from the interfacial potential barriers. This also reduced the additional resistance as well as the threshold current of the MM-VCSEL caused by the interfacial potential barriers between adjacent layers in the bottom and top DBR mirrors. To perform the photon and carrier confinement for index/gain guiding and transverse-mode number limitation, the bilayer Al0.96Ga0.04 As oxidation was performed within the central part of the p-type DBR mirror for isolating the current flow outside the desired lasing area, where electron mobility became much higher than the hole mobility to effectively restrict electron—hole recombination.

However, the differential resistance significantly increased with decreasing emission aperture size, which seriously degraded the differential quantum efficiency by enlarging the power consumption and deteriorating the signal-to-noise ratio (SNR) of modulation. In addition, the aperture size of the MM-VCSEL not only set a trade-off among mode number (field distribution), output power (quantum efficiency), and modulation bandwidth (temporal resolution) but also affected the carrier lifetime and the heat dissipation (for efficient recombination and modulation). With designing a mesa size of 20 μm and an aperture size of 7.5 μm, a compromise was offered among modulation speed, output power, and spectral linewidth. Finally, a thin benzocyclobutene (BCB) film was deposited to passivate the MM-VCSEL surface. In comparison with typical SiO2 and polyimide passivation, the BCB passivation layer exhibited a relatively low dielectric constant to shorten the charging/discharging time of the VCSEL for effectively improving its switching speed, which also provided other advantages including low transmission loss and high thermal stability. A ceramic mount with Au-plated coplanar GS stripline electrode was used to pack the MM-VCSEL chip, in which the Ag glue was coated on the back n-side for adhering to the ground pad and the eight-wire parallel bonding scheme was used on the top p-type for connecting to the signal pad.

Figure 1c illustrates the flat-end-face polished-fiber diagnostic system for analyzing the localized power, pulsewidth, and delay time at different positions of the 2D commercial MM-VCSEL array. A GS microprobe was touched to the coplanar stripeline electrode with 250 μm pad spacing for driving the 940 nm MM-VCSEL array accommodating more than 600 MM-VCSEL elements with a chip size of 1 mm². For continuous-wave (CW) operation analysis, a direct current (DC) current source (Thorlabs, LDC-210) with a compliance voltage meter was used to scan the P–I and V–I responses of the MM-VCSEL. Then, a 100 MHz sinusoidal-wave signal with a peak-to-peak amplitude of up to 1 V for small-signal modulation was synthesized from an arbitrary wave generator (AWG, Tektronix 7122B) with its analog bandwidth of 5.3 GHz and sample rate of 12 GS s⁻¹, which was further boosted by 26 dB in a wideband amplifier (Mini-circuits, ZHL-2-12-+) for electrical pulsation via an electrical comb generator (HP, 33002A) at a repetition rate of 100 MHz. Next, a wideband bias-tee (Marki, BT1-0026) was utilized to combine the DC bias at V_DC = 300 mA and the alternating current (AC) pulse at V_pp = 15.3 V for large signal driving the MM-VCSEL. According to the pulsed modulation principle, the DC bias was set nearly or below the threshold of the MM-VCSEL array to obtain the best optical pulsation without pedestal pulses. Afterward, the DC bias offsetted the electrical pulse to drive the MM-VCSEL array via a 40 GHz broadband coplanar GS probe (CASCADE, ACP40-SG-450) with a pitch interval of 450 μm. To persistently maintain the ambient device temperature at 20 °C, the feedback-controlled thermoelectric (TE) cooler and the water-cooled heat sink (Deryun, DFC-4PT03) were used for dissipating heat from the MM-VCSEL array chip during operation. At the transmitting node, the emission output of the MM-VCSEL array was collected using a flat-end-face polished multimode fiber (MMF, WT&T). At the receiving node, an avalanche photodiode (APD, NECSEL) with a sensitivity of 5 A W⁻¹ under a DC voltage bias of 180 V was used for optical-to-electrical converting of the received pulsed stream. Another wideband bias-tee (Tektronix, PSLP5530B) was utilized to extract the electrical pulsed signal before its analysis in a digital serial analyzer (CSA, Tektronix 8200) with a 20 GHz (Tektronix, 80E03) module.
3. Results and Discussions

3.1. Lasing and Modulation of the MM-VCSEL Array

Using the flat-end-face polished MMF probe for power collection, Figure 2a shows the $P$–$I$ and differential curves by partially picking up a localized region (with the emission from only one MM-VCSEL element) of the MM-VCSEL array under the CW operation. After coupling into the flat-end-face polished MMF probe, threshold current ($I_{th}$) of 350 mA, the slope efficiency ($dP_{out}/dI_{bias}$) of 1.2 ± 0.2 mW/A, and the CW lasing power of 0.8 mW at DC bias of 1 A before saturation are indicated.

Note that the upper limitation of the DC bias current for the former experiments including the pulselwidth and delay time analyses was set at nearly the threshold current ($I_{th}$) of the MM-VCSEL chip due to the need for the optical pulsation with the shortest pulselwidth. By including the coupling ratio ($\eta_{MMF}$) of the MMF probe which only picks up the localized MM-VCSEL element, and combining the differential quantum efficiency of the MM-VCSEL element ($\eta_{d} = (q/h
u)dP_{out}/dI_{bias} = (q/h\nu)\eta_{ext,MMF}$) for the MM-VCSEL element, the measured quantum efficiency of such an MMF-coupled MM-VCSEL module is calculated as 0.091% ($\eta = \eta_{MMF}\eta_{d}$), where $q$, $h$, and $\nu$ respectively denote the electron charge, the Planck’s constant, the device frequency, the external quantum efficiency, and the internal quantum efficiency of the MM-VCSEL element. Figure 2b exhibits the $V$–$I$ and its differential response of the MM-VCSEL element. At the bias current of 315 mA ($< I_{th}$), the differential resistance determined as 0.72 $\Omega$ for the MM-VCSEL array is far from 50 $\Omega$ when considering the impedance matching with the input circuit for electrical pulse generation. The resistance slightly drops to 0.52 $\Omega$ as the current increases to urge the lasing of more than 600 parallel-connected elements in the 2D-aligned MM-VCSEL array.

Figure 2b illustrates both the variation of the dynamic and adiabatic chirps of the MM-VCSEL array biased at different DC currents are analyzed to confirm the 1-bit nonreturn-to-zero on–off keying (NRZ-OOK) waveform overshooting phenomenon appearing on the rising and falling edges, as shown in Figure 3. In contrast to the blue line showing the pulse waveform, the red line in Figure 3 exhibits both the variation of the dynamic and adiabatic chirps as a function of time. When DC biasing the MM-VCSEL array below 350 mA, most of the elements are not lasing, so the small output contributes to the weak modulation chirp. By increasing the DC bias from 350 to 370 mA, the DC current turns the VCSEL from below threshold to the nearly threshold condition, enabling the whole electrical pulse bias to be offset to beyond the lasing threshold. Such an upshift of the DC bias level significantly enhances the dynamic frequency chirp, because the transient phase change $d(\phi)/dt$ is proportional to $dP(\phi)/dt$ by increasing the electrical pulse amplitude beyond the threshold bias. Therefore, the on/off extinction ratio (ER) of the optical pulse is also increased to result in the larger transient and adiabatic chirps. Increasing the DC bias beyond 370 mA observes the decaying trend of the dynamic frequency chirp accompanied with the decreasing waveform amplitude of the MM-VCSEL array output. As the DC bias increases, while the pulse amplitude remains unchanged, the
average power of the VCSEL increases but its differential resistance deviates farther away from 50 Ω to cause a much larger power reflection. These effects effectively generate the smaller derivative of transient power and the larger average power to contribute to the lower on/off ER and the chirper frequency concurrently. The formula for analyzing the chirp effect of the encoded output can be described as

$$\frac{d\phi(t)}{dt} = \frac{\Delta\nu(t)}{4\pi} \left[ \frac{1}{P(t)} \left( \frac{dP(t)}{dt} \right) \right]$$

where $\phi(t)$ denotes the output phase, $\Delta\nu(t)$ the frequency deviation, $\alpha(t)$ the chirp parameter, and $P(t)$ the power of the MM-VCSEL. The larger chirped frequency deviation with the higher overshooting waveform and the longer damping period is observed at the lower DC bias. In definition, the dynamic chirp usually locates at the rising and falling tails and the adiabatic chirp refers to the frequency gap at two levels of “0” and “1” bits. Even with increasing DC bias current of the MM-VCSEL array, the adiabatic chirp within the on-/off level of the encoded NRZ-OOK output remains extremely small in comparison with the significant change in the dynamic chirp. Only the dynamic chirp with transient frequency variation of up to GHz can be observed, whereas almost no adiabatic chirp is seen in the on-bit region of the pulse waveform. In detail, such a tiny adiabatic chirp reveals a frequency variation ($\approx 15$ MHz) by two orders of magnitude smaller than that of the dynamic chirp. According to the study by Saravanan et al., the adiabatic chirp

Figure 3. The 1-bit waveform shape for chirp measurement on the MM-VCSEL array. The waveform shape (blue line) and dynamic frequency chirp (red line) of a 100 Mbit s$^{-1}$ 1-bit pulse modulated onto the MM-VCSEL array at different biases.
indicates the lasing frequency difference between the on and off states under CW operation, which is only affected by the power fluctuation with changing core temperature and the free-carrier concentration of the VCSEL array in both states. This explains why the adiabatic chirp is much smaller than the transient chirp, as the output power of the VCSEL array remains stable at the always-off ("0" bit) or always-on ("1" bit) state under CW operation in a certain time slot. As a result, the positive frequency change on the rising edge and the negative frequency change on the falling edge cause the MM-VCSEL array to show a negative chirping behavior under modulation. With further enlarging the DC bias current from 350 to 800 mA, the 1 bit data encoded on the MM-VCSEL array attenuates its overshooting peak power from 0.17 to 0.05 μW with a slope of −0.26 nW mA⁻¹ (as obtained by measuring the amplitude overshoot from the average of the "1"-bit waveform at the rising part), indicating that the overall chirped frequency range suppresses from −1 to −0.4 GHz at the rising edge of the encoded waveform.

Figure 4 summarizes the variations of dynamic frequency chirp values for one element in the MM-VCSEL array under different biased currents, where the black line represents the chirp frequencies at positive parts and the green line represents those at negative ones. Note that the positive value of the dynamic frequency chirp in the rising part shrinks from 0.7 to 0.34 GHz, and the negative value of the dynamic frequency chirp in the falling tail enlarges from −0.51 to −0.38 GHz when increasing the DC bias current from 370 to 800 mA. With the chirp parameter defined as \( \alpha = 4\pi \Delta \nu \text{d}[\ln P]/\text{d}t \)⁻¹, the overall negative chirp frequency variation (from leading edge to the trailing edge of the modulated waveform) of the MM-VCSEL array is reduced from −1.21 to −0.72 GHz when increasing the DC bias from 370 to 800 mA.

Later on, the Smith chart of the \( S_{11} \) parameter is performed to analyze the impedance mismatched condition of the MM-VCSEL array DC biased at 315 mA. In Figure 5, most of the measured \( S_{11} \) data is concentrated in the lower part of the Smith chart, indicating that this MM-VCSEL array is a capacitive element. The \( S_{11} \) curve in the Smith chart is located near the point \( \Gamma = 1 \) at the low-frequency region, representing the almost short-circuit situation with nearly 100% reflection, as confirmed by the CW operation results shown in Figure 5. When the operating frequency increases, the spiral curve appears on the Smith chart because of the resonance and transmission line effect inside the MM-VCSEL array.

Such an MM-VCSEL array reveals a gradually decreased series capacitance with increasing frequencies and is accompanied with a resonance contributed by the decreasing shunt inductance at high frequencies, as correlated with the corresponded spectra of real and imaginary parts of the \( S_{11} \) parameter, showing correlated resonant peak amplitude and a discontinuous phase at a certain frequency of about 0.9 GHz. Regarding the spiral—curve generation in the Smith chart, the larger phase difference is enhanced by enlarging the ratio of the transmission line length to the operating wavelength by increasing the frequency (reducing the wavelength) or lengthening the transmission line. Figure 6a,b shows the real and imaginary parts of the equivalent impedance \( Z(f) \) by extracting from the \( S_{11} \) response using the formula described as \( Z(f) = Z_0[1 + S_{11}(f)][1 - S_{11}(f)] \)⁻¹, in which \( Z(f) \) denotes the load impedance varying with frequency. The measured real and imaginary parts of the equivalent impedance indicate the effective resistance and reactance, respectively.

The low-frequency capacitance of the MM-VCSEL array is measured as 380 pF using a C=V meter with its analog bandwidth of 10 MHz, which is in good agreement with the respective inductance and capacitance of 0.08 ohm and 398 pF extracted from the S-parameter chart at the same frequency. With increasing the modulation frequency from 10 to 100 MHz where the pulsed modulation is repeated periodically, the inductance significantly increases to 0.2 and the capacitance accordingly decreases to 160 pF under vector analysis. Indeed, the
Moreover, the frequency-dependent bandwidth of only 0.8 GHz during large-signal encoding for practical ToF applications. This leads to a future challenge on the specific design of the electrical pulsed driving circuit with ultralow output impedance to feed the whole electrical pulse into the MM-VCSEL array without suffering from the impedance mismatched reflection. Otherwise, the reflected signal forms multiple reflections to interfere with each other among the laser diode, the transmission line, and the driver sites. This eventually induces intersymbol interference (ISI) and increases the timing jitter. Especially, when the reflection is caused by the mismatch between the terminal impedance and \(Z_0\) of the transmission line, the reflected signal will be added to the incident signal to further degrade the data transmission.

With numerical simulation in detail, Figure 7 shows the equivalent circuit model for the MM-VCSEL array with corresponding resistors, inductors, and capacitors. In this model, the parameters \(R_0\) and \(C_m\) denote the submont resistance of 50 \(\Omega\) and the capacitance of 0.4 \(\text{pF}\) for the packed MM-VCSEL array. By neglecting the inductance of the metallic contact pads \((L_p)\) connected to the MM-VCSEL array, the pad capacitance \(C_p\) and \(R_p\) for metal contacts on benzoxylobutene (BCB) are determined as 0.07 \(\text{pF}\) and 1 \(\Omega\), respectively.\(^{24}\) In previous works,\(^{25–28}\) the shunt resistance exists in the polyimide region, as defined by \(R_{\text{shunt-polim}}\) in this work. The shunt resistance is assumed as 1 \(\Omega\), which is located in the equivalent circuit model.\(^{25–28}\)

In addition, \(R_{\text{cont}}\) and \(L_{\text{cont}}\) respectively denote the contact resistance and inductance with corresponding values of 00 \(\Omega\) and 1.7 \(\text{nH}\). Among them, \(L_{\text{cont}}\) is also accompanied by a resistance of 0.21 \(\Omega\). \(C_t\) is the total parasitic capacitance of 19 \(\text{pF}\) contributed by the oxidized aperture capacitance and intrinsic layer capacitance located below the oxidized aperture. \(C_i\) denotes the combination of diffusion capacitance and depletion capacitance with a simulated value of 19 \(\text{pF}\). Finally, \(R_t\) represents the junction resistance in the active region with a simulated value of 13 \(\Omega\). All the fitting parameters of the MM-VCSEL array bonded on the Au coplanar stripline-coated ceramic submount are summarized in Table 1. With these parameters, the fitting curve in Figure 5 exhibits a good agreement with the experimental curve.

### 3.2. Transmission Performance and Delay Time Measurement of Eight-Wire-Bonding MM-VCSEL Array

To drive the MM-VCSEL at optical pulsation, a 100 MHz sinusoidal wave generated by the AWG is boosted by an amplifier (Mini-Circuits, ZHL-2-12+) with a power gain of 26 \(\text{dB}\). This generates a pumping signal with its power of 30 \(\text{dBm}\) to drive a 100 MHz comb generator for obtaining the electrical pulse, as shown in Figure 8a. As a result, the electrical pulse exhibits a peak-to-peak voltage \((V_{\text{pp,elec}})\) of 15.3 \(\text{V}\), a rising time of 79.2 ps, a fall time of 212 ps, and a pulsewidth of \(\Delta_{\text{pulsewidth}} = 126.9 \text{ps}\). Unfortunately, the secondary electrical pulse pedestal with a \(V_{\text{pp,ped}}\) of 5.1 \(\text{V}\) appears at only 0.4 ns far from the main peak of the electrical pulse. Figure 8b shows the uniformity analysis on the pulsed-modulated MM-VCSEL array, as monitored by the beam profiler (Newport, LBP2-HR-VIS2). Owing to the serial inductance of the MM-VCSEL array, the emission contour profiler of the 2D MM-VCSEL array reveals the brighter emitting patterns for the elements closer to the electrical probe, and other elements
in the whole emission area can provide similar peak power after driving with the electrical pulse generated from the comb.

For pulsewidth and delay time analyses, Figure 9 illustrates the optical pulses contributed by localized VCSEL elements detected from the different positions of the MM-VCSEL array under the pulsed-modulating operation at a DC bias of 315 mA (≈0.9 Ith). To facilitate the recognition of the position dependency, Lx is used to represent different corners located on four edges of the MM-VCSEL array. According to the diameter of the optical fiber, Lx is defined as an area containing nearly nine single MM-VCSEL elements. By collecting the emitting light with the MMF probe moved from L1 to L2, L3, and L4 in turn, the corresponding waveform shape and arrival time of the localized optical pulses are recorded and compared with each other in the surrounding figures of Figure 9. After electrical-to-optical modulating of the MM-VCSEL array, the detected optical pulse exhibits power attenuation as large as 56 dB during conversion when comparing with the power of the electrical pulse. As compared to the original electrical pulse, nearly 99% of the power is reflected because of the impedance mismatching between the signal source end and the MM-VCSEL array. From a microwave reflection coefficient of –0.97 and a microwave return loss of 0.265 dB measured for the MM-VCSEL array under sinusoidal-wave modulation, only 6% of the power of the electrical pulse is expected to send into the VCSEL array under pulsed modulation. Therefore, nearly 94% power of the electrical pulse will be reflected from the MM-VCSEL array because of the impedance mismatching between the driving circuit and the MM-VCSEL array. Moreover, the highest converted Vpp after the electrical-to-optical conversion from the output of the nearly nine single MM-VCSEL elements in the MM-VCSEL array is measured as only 25.1 mV. As compared to the original electrical pulse with Vpp of 15.3 V in Figure 8, the Vpp of the converted

Table 1. Values of the circuit simulation process of the eight-bonding MM-VCSEL array chip.

| Symbol         | Meaning               | Values@315 mA |
|----------------|-----------------------|---------------|
| Rm             | Submount resistance   | 0.1 Ω         |
| Cm             | Submount capacitance  | 0.4 pF        |
| L              | Metal track inductance| 0 nH          |
| Rshunt-poly    | Polyimide shunt resistance| 1 TΩ    |
| Rp             | Pad resistance        | 0.1 Ω         |
| Lp             | Pad inductance        | 0 nH          |
| Cp             | Pad capacitance       | 0.07 pF       |
| Rcont          | Contact resistance    | 0 Ω           |
| Cp             | Parasitic capacitance | 19 pF        |
| Rj             | Junction resistance   | 13 Ω          |
| Lcont          | Contact inductance    | 1.7 nH and 0.21Ω |
| Cj             | Junction capacitance  | 19 pF         |
Because the $L_1$ position is closest to the microwave probe which brought the electrical pulse, the single VCSEL element can deliver the highest $V_{pp,\text{opt}}$ of 25.1 mV and the narrowest pulsewidth of $\Delta t_{\text{pulselength}} = 601.8 \text{ ps}$ as picked up from the nearest to the probe at the $L_1$ site. The APD used in this work exhibits a bandwidth of 3.5 GHz with an equivalent impulse response of about 130 ps in the time domain. Such an impulse response is sufficiently short as compared to the pulsed-modulated pulsewidth of 601.8 ps generated from the VCSEL array. To deconvolute the real pulsewidth from the measured pulsewidth using $t_{\text{real}} = (t_{\text{measured}} - t_{APD} - t_{\text{scope}})^{0.5}$, the deconvoluted pulsewidth is obtained as 588 ps. The difference between the measured and deconvoluted pulsewidth is quite small. The shortest rising and falling times of the detected optical pulse are, respectively, measured as 386.0 and 605.1 ps. Meanwhile, a secondary pulse after the main optical pulse also appears at a relative delay of $\Delta t_{\text{delay}} = 1.76 \text{ ns}$ and a peak amplitude of $V_{pp,\text{2nd}} = 11.3 \text{ mV}$. The optical pulsewidth is five times longer than the electrical one, which facilitates the best spatial resolution as $\Delta L = C(\Delta t_{\text{pulselength}}/2) = 9 \text{ cm}$, with $C$ denoting the light speed in general for ToF ranging applications. When moving the detection site to $L_2$ that is on the same side but separated from $L_1$ by 1 mm, the $V_{pp,\text{opt}}$ of the main optical pulse emitted from a single-element VCSEL is slightly decreased to 22.3 mV with its slightly broadened pulsewidth of 618.6 ps and the rising/falling times of 408.9/620.5 ps. Similarly, a secondary pulse also appears with the same delay of $\Delta t_{\text{delay}} = 1.76 \text{ ns}$ after the main pulse but a weaker peak amplitude of $V_{pp,\text{2nd}} = 10.5 \text{ mV}$. In contrast, when moving the detection point to $L_3$ and $L_4$ positions, which are far from the electrical probe and bonding wire, the driving electrical pulse inevitably suffers from a current attenuation caused by the parallel-connected VCSEL elements to further generate the broadened optical pulses with relatively weakened optical power. At the $L_3$ position, the detected optical pulse greatly attenuates its amplitude to 6.8 mV accompanied with its pulsewidth broadened to 644.1 ps and rising/falling times of 439.3/643.81 ps.

As the main optical pulse is detected from one VCSEL element located at the $L_4$ region, its pulsewidth broadens to

![Figure 9. Pulsewidth and delay time analysis of the optical pulses generated from four corners of the MM-VCSEL array. The pulsewidth and delay time analysis and comparison of the optical pulses generated from four corners of the MM-VCSEL array.](image-url)
Δt_{pulselength} = 672.61 ps with a decayed amplitude of V_{pp, \, opk} = 8.6 mV and reveals rising/falling times of 603.9/456.8 ps. For these two cases driven far away from the electrical probe, their secondary optical pulses all merge into the noise background due to the overall degradation of the pulsed amplitude. In comparison with the detected optical pulses for four corners of the MM-VCSEL array by plotting any adjacent two waveforms in the sub-figures of Figure 9, the relative time delay between two detected optical pulses generated from the VCSEL element at different Lx positions can be analyzed precisely. As both L1 and L2 positions are allocated on the same side of the coplanar stripline contact and closest to the electrical probe, a very small delay of Δt_{L1, L2} = 54 ps is observed. In contrast, the MM-VCSEL array with combining effects of capacitance and inductance parallel-connected VCSEL elements causes the delay time of pulses between L1 and L2 positions lengthened to Δt_{L1, L3} = 204.4 ps. Compared with the pulses from L1 and L4 positions leading to the largest delay of Δt_{L1, L3} = 273.4 ps because of the farthest distance of the electrical pulse traveling to the detecting point at L4. These analyses observe the ultimate limitation of the pulsed-modulated optical pulse set by localized elements in the MM-VCSEL array. To convey the general electrical and optical requirements of VCSELs as ToF emitters, the related parameters are extracted from the specification datasheet of the commercial standard ToF module manufactured by Lumentum[29] and from the IEC60825-1 standard,[30] as shown for comparison in Table 2.

In addition, the parametric comparison among previous reports, commercial products, and our results from academic institutions and industrial companies are also summarized in Table 2,[31–33] indicating that the proposed pulsation for the VCSEL array exhibits its output superiority on the shortened pulselength and rising/falling time which are well below the criterion set by the international electrotechnical commission (IEC) standard. From this parametric comparison, the proposed operation for the VCSEL array exhibits its output superiority on the shortened pulselength and rising/falling time well below the criterion set by the IEC standard.

Most of the common high-power VCSEL arrays commercially available for ToF sensing applications used in consumer electronics are almost designed in vertical contact geometry on the market. That is, the p- and n-type electrodes of the high-power VCSEL array are, respectively, designed on the top and bottom surfaces. The packaging process includes die bonding and wire bonding to additional contact pads with a much larger wiring area, which inevitably increases the R/L/C elements into the equivalent circuit of the VCSEL array to lengthen the switching time. Packaging the VCSEL array in a flip-chip mount design has the opportunity to solve the aforementioned problems caused by the vertical structure design, which excludes the need for wire bonding on the emitting surface to form the VCSEL array with the smallest size.[34–35] In addition, the elimination of metal wire bonding can further reduce the parasitic inductance to speed up the rising/falling times and thereby improve the ToF sensing performance. Moreover, the flip-chip-mounted VCSEL array can directly etch the microlens upon the emitting surface to achieve beam shaping with the controlled divergence of each VCSEL element for realizing all-solid-state beam steering. In terms of thermal performance, the flip-chip-mounted VCSEL array can directly attach its electrode to the heat sink of the package because of the removal of the epitaxial substrate at the bottom side, which enables the efficient heat transfer to improve the slope efficiency, the thermal resistance, the saturated power, the thermal roll-over current, and even the switching response, making it very competitive with the current design. In contrast, although there is still not a specific design on the transmission-line submount to alleviate the impedance mismatch issue at the current stage, it is expected to add a tapered impedance design for serving as an auxiliary impedance matching element between the driving circuit and the VCSEL array for achieving the proper feeding capability.

### 4. Conclusion

The comparison of localized optical pulselength and delay time responses among the VCSEL elements in a 940 nm MM-VCSEL array under the pulsed-modulating operation is demonstrated to realize the pulsed performance of the MM-VCSEL array. With more than 600 single VCSEL elements composed in the MM-VCSEL array, the MM-VCSEL array Au wire bonded on the ceramic submount with Au-plated coplanar stripline pads exhibits a threshold current of 350 mA and a slope efficiency of 1.2 mW A^{-1}. Using a flat-end-face polished MMF probe to collect the optical power, the single VCSEL element in the MM-VCSEL array reveals its maximal optical power enlarged from 1.25 to 0.8 mW and differential resistance reduced from 1.8 to 0.5 Ω with the bias current increasing from 0.01 to 1 A. By setting the DC bias at 315 mA (≈0.9 Ith) for optimizing the pulsed modulation, the impedance of 0.72 Ω for the MM-VCSEL array causes the almost entire reflection of the modulation with Γ of −0.97 because of the large impedance mismatch between the circuit load and the MM-VCSEL array. By analyzing the overshooting of the 100 Mbit s^{-1} data-bit waveform encoded on the MM-VCSEL array at different DC biases, the dynamic frequency chirps at rising and falling parts reduce from 0.7 to 0.34 GHz and from −0.51 to −0.38 GHz, respectively. This contributes to the overall chirping parameter from −1.2 to −0.4 GHz when enlarging the DC bias of the MM-VCSEL array from 370 to 800 mA. The S_{11} trace reveals a clockwise spiral curve in the lower half part of the Smith chart to corroborate the dominated capacitive response, significant modulation reflection, and degraded bandwidth for the packed MM-VCSEL array under large impedance mismatch. Finally, the optical modulated pulsation is performed by a boost-amplified electrical comb driving the MM-VCSEL array with a large electrical pulse amplitude of 15.3 V and pulselength of 126.9 ps. With a finite modulation

### Table 2. The key parameters for the VCSELs as ToF emitters from different academic and industrial institutions.

| References | λ (nm) | P_{out} (W) | θ_{θθ} | τ_{switch} (ns) | t_{rising/falling} (ns) | Eye safety@Class 3B |
|------------|-------|------------|-------|----------------|------------------------|---------------------|
| [29]       | 940   | 3.2        | 21°   | 20 ns          | 500/500 ps            | 800 mW              |
| [31]       | 940   | 2.5        | 25°   | 110 μs         | 1/1 ns                | 800 mW              |
| [32]       | 850   | 13         | –     | 2.5 ns         | 180/180 ps            | 800 mW              |
| [33]       | 940   | 10         | 18°   | –              | –                      | 800 mW              |
| This Work  | 940   | 2.4        | 22 ± 1°| 588.8 ps      | 386/601 ps            | 800 mW              |
bandwidth of 0.8 GHz for the MM-VCSEL array biased at 0.9 I_{th},
the lasing beam profile analysis of the pulsed-modulated MM-
VCSEL array observes the slightly higher intensity distributed
near the microwave probe and bonding wire than those at other
positions. The localized probing of the pulsed-modulated optical
pulsation response shows the strongest pulse with an amplitude
of 25.1 mV and pulselength of 601.8 ps from the single element at
localized positions of the MM-VCSEL array. Moving the probe to
other positions far away, the probe obtains additional delay time
as large as 273.4 ps on starting up the pulsed-modulated optical
pulsation. Owing to the differential responses contributed by the
localized elements in the MM-VCSEL array, the broadened pul-
sewidth and lengthened time delay set a limitation on the reso-

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the
responding author upon reasonable request.

Keywords
delay time, multimode vertical-cavity surface-emitting laser arrays, optical
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