In the streak tube laser imaging system, there are two conflicts: the first is between high spatial resolution and wide field of view (FOV). The second is between high temporal resolution and deep depth of field (DOF). In this paper, a new non-scanning streak tube laser imaging system is presented. A microlens array with three different apertures is used to non-uniformly collect data from the image plane so the conflict between high spatial resolution and wide FOV is relieved and the detectable range of system is also increased. A remapping fiber optics with special design is used to realign the image plane on the two photocathodes of streak tubes to realize the operation mode of the two streak tubes so the conflict between high temporal resolution and deep DOF is relieved. The mathematical model of the entire imaging system is established based on the range equation. The structure parameters of the receiving optical system are optimized in order to achieve the optimal utilization rate of light energy. In the third, three simulated contrast experiments are organized, and the experiment results demonstrate that the imaging system proposed in this paper possesses properties of higher spatial resolution, wider FOV, higher temporal resolution, deeper DOF, and larger detectable range.

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OCIS codes: (110.2350) Fiber optics imaging; (110.6880) Three-dimensional image acquisition; (280.3400) Laser range finder; (040.1880) Detection.

https://doi.org/10.1364/AO.56.000487

1. INTRODUCTION

The three-dimensional laser imaging technique has emerged as a key technology for capturing target data. Recently, it has been used extensively in a variety of fields such as target recognition, robotics, terrain visualization, medical diagnostics, and vehicle navigation [1–4]. Generally, three-dimensional laser imaging systems can be divided into two categories: scanning and non-scanning types [5,6]. The imaging speed of a scanning laser imaging system is low due to the existence of the scanning structure. The non-scanning laser imaging system has a simple structure and high imaging speed compared with the scanning type [7]. The multi-slits streak tube imaging lidar (MS-STIL) is one of the diverse non-scanning laser imaging systems and has numerous qualities such as a high frame rate, abundant information acquisition, and strong anti-interference performance [8,9]. Therefore, the MS-STIL is regarded as one of the most promising three-dimensional laser imaging systems [8,10].

In 1989, Knight first introduced the MS-STIL [11]. In 2000, Gleckler established the equation for range resolution of the STIL and presented several system configurations of the STIL with different applications [12]. In 2001, he proposed a MS-STIL for capturing laser-induced fluorescence images [13]. In 2003, Nevis developed a fully automated process of the STIL that rendered a stripe image into intensity and range images and carried out a real experiment with the STIL on an underwater object [14]. In 2003, he showed a series of imaging results of STIL on underwater target [15]. In 2009, Wang proposed a lidar equation based on the Lambert law and finished an imaging experiment of the MS-STIL from 2500 m away and with 23 km visibility [16]. In 2012, Yang and Wu investigated the signal-to-noise performance of STIL within the framework of the linear cascaded systems theory and analyzed some factors that limit the signal-to-noise performance of the external intensified STIL system [17,18]. In 2013, Wei proposed a method used to accurately measure the minimum detectable energy density of a streak tube using a photon counter [19]. In 2013, Sun proposed a new polarized STIL, which could collect two polarization images, provide polarization angles, and carry out far distance imaging experiments in which the part’s target was hidden in the clutter [20]. In 2014, Tian developed a control and imaging process for the
STIL using VB and MATLAB and carried out an experiment in which range resolution was better than 2 cm [21]. In 2014, Gao described a STIL used to detect short scale surface wave fields and demonstrated feasibility of this system by organizing real experiments in the East Sea and South China Sea [22]. In 2014, Jiang proposed an adaptive Gaussian-guided filter for noise removal and detail enhancement of stripe images and experimentally demonstrated its capacity to preserve edges and thin structure [23]. In 2015, Gao carried out imaging experiments of the STIL, in which range resolution was 2 cm under laboratory conditions, less than 0.65 m under outdoor imaging tests (4 km), and 1.5 cm for underwater targets [24]. In 2016, Ye investigated the effect of time bin size on the range accuracy of the STIL and carried out an indoor experiment for a planar target [25]. In 2016, he investigated the range accuracy of the STIL based on a peak detection algorithm including the effects of blurring the stripe image [26].

In the application of the MS-STIL, we always have some special requirements for the streak tube. A larger effective area of the photocathode is required in order to provide higher spatial resolution and wider field of view (FOV); the larger effective area of the phosphor screen is required in order to provide higher temporal resolution and deeper depth of field (DOF); and stronger sensitivity of the photocathode is also required in order to get a larger detectable range [9, 27]. To get a higher spatial resolution in the MS-STIL, the diameter of fibers used to collect data on the image plane of the receiving optical system should become as small as possible. However, this will lead to a decrease of the FOV area when the number of fibers remains unchanged. When the diameter of the fiber decreases, the light received by each fiber will also reduce, which shows that the detectable range of the system is also decreased. In order to get a higher temporal resolution, the sweep voltage in the streak tube should become steeper, which will lead to a decrease of DOF when the number of time bins corresponding to each time-resolved channel is unchanged. Therefore, in the MS-STIL, there are two conflicts. The first is between high spatial resolution and wide FOV; the second is between high temporal resolution and deep DOF. The DOF of STIL is small compared with other laser imaging systems. But the basic imaging principle of the MS-STIL makes its DOF smaller because each fiber has a corresponding area in the phosphor screen, and the area of each time-resolved channel is smaller than that of the SS-STIL [21, 26]. Furthermore, a large detectable range is also a desired and important property. Therefore, how to relieve these two conflicts and improve the detectable range is an important research subject.

In the regular MS-STIL, there is no microlens array in the front of the remapping fiber optics, and the remapping fiber optics are directly used to uniformly collect data from the image plane. Also, the entire system runs in a single streak tube mode [8, 9]. The non-uniform sampling pattern, which comes from bionic technology, is an outstanding method that can encode a wide FOV with variable spatial resolution. This technology can relieve the conflict between high spatial resolution and wide FOV. Recently, our team presented a log-polar 3D laser imaging system based on the scanning principle in [28]. We have also presented a log-polar 3D laser imaging system based on the non-scanning principle in [7, 29]. In this paper, a new non-scanning streak tube laser imaging system that belongs to a kind of MS-STIL is presented. It successfully relieves the conflicts between high spatial resolution and wide FOV and between high temporal resolution and deep DOF. It also increases the detectable range of the system. Compared with regular MS-STIL, a microlens array with three different apertures and a remapping fiber optics with special design are introduced into a new imaging system. The effect of these two new components on temporal resolution and range resolution is analyzed by the modulation transfer function (MTF). The mathematical model of the entire imaging system is established based on the range equation. The structure parameters of the receiving optical system are optimized in order to achieve an optimal utilization rate of light energy. Finally, three simulated contrast experiments are organized in order to verify the conclusions.

2. THEORY
A. Imaging System
The schematic of the proposed imaging system is shown in Fig. 1. This system includes the following: pulse laser, transmitting optical lens, mirror, receiving optical lens, microlens array, remapping fiber optics, streak tube, charge coupled device (CCD), and computer. The pulse laser can transmit narrow laser pulse beams with a small divergence angle after receiving the trigger signal. The transmitting optical lens has two functions: beam shaping and beam expanding. The mirror has a 45° inclined angle versus the optical axes of the transmitting optical lens and receiving optical lens, so these two lenses partially share a common optical axis. The receiving optical lens is a kind of reflecting telescope with a long focal length and a large aperture. The microlens array with three different apertures is located on the image plane of the receiving optical lens, and it is used to realize a non-uniform sampling pattern. The remapping fiber optics are manufactured using numerous fibers, and the front-end spliced pattern corresponds to that of the microlens array. At every focus point of the microlens array, there is a fiber. But the back-end of the remapping fiber optics is segmented into two parts, and every part is coupled to the photocathode of the streak tube. The streak tube is a kind of device with high temporal resolution. The CCD should meet the requirements of the fast shutter speed, low dark current, and abundant pixels. The computer is used to control the operation time sequence and process the stripe image. In order to improve the stripe image quality, all of the components in this imaging system should have good compatibility.

The working process of the entire system can be divided into the transmitting process and the receiving process. The transmitting process is as follows. The computer sends a trigger signal to the pulse laser and, after a time delay, four trigger signals are sent to two streak tubes and two CCDs. After the pulse laser receives the trigger signal, it begins to transmit the laser beam. The laser beam first undergoes beam shaping and beam expanding of the transmitting optical lens, and then its propagation direction is turned 45° by the mirror. Finally, this laser beam illuminates the desired target area. The receiving process
is as follows. The back-scattering laser is collected by the receiving optical lens and then forms an image on the image plane of the receiving optical lens. The image of the target on the image plane is non-uniformly sampled by the microlens array; then the laser energy collected by each microlens converges into the corresponding fiber. Next, the remapping fiber optics re-map these laser beams to different areas of the photocathode of the two streak tubes. At this moment, these two streak tubes begin to work under the control of the trigger signal from the computer. The laser pulse is converted into an electrical pulse signal by the photocathode, and the laser pulse and the electrical signal have the same space-time structure. All of the electrical signals will be converted into two stripe images on the two phosphor screens. Then, these two stripe images are collected by the CCDs under the control of trigger signals from the computer. Last, the computer reconstructs the range image and the intensity image using an effective processing algorithm. Now, a round of the imaging process ends, and the computer can begin to arrange the next round of the imaging process.

**B. Microlens Array**

The space-variant sampling pattern gives consideration to spatial resolution and FOV, and it can encode a wide FOV with variable spatial resolution [30]. In this paper, a microlens array with three different apertures is used to non-uniformly collect data from an image plane; its structure is shown in Fig. 2. The ratio of diameters of these three kinds of microlenses is 1:2:4. If we assume that the ratio of ring numbers of these three kinds of microlenses is \( n_1:n_2:n_3 \), the total number \( N \) of microlenses is

\[
N = 4n_1^2 + 4n_2^2 + 4n_3^2 + 4n_1n_2 + 4n_2n_3 + 2n_1n_3. \tag{1}
\]

This array needs to be positioned on the image plane of the receiving optical lens, and every microlens has the same focal length. In the center area of this array, microlenses with a minimum diameter are used to sample the image, and the area with the highest spatial resolution is called the recognition area, which can be applied to target tracking and target recognition. In the outside of the recognition area, the microlenses with a medium diameter are used to sample the image, and this area with the medium spatial resolution is called the transition area. In the outermost area of this array, microlenses with a maximum diameter are used to sample the image, and this area with the lowest spatial resolution is called the searching area, which can be applied to make a decision about whether there is an object in the FOV. In this area, the diameter of microlenses is the largest. Therefore, each microlens can receive more laser energy, which means that the searching range of the system becomes greater. Compared with a space-invariant sampling pattern, the space-variant sampling pattern possesses a higher spatial resolution, wider FOV, and larger detectable range.

**C. Remapping Fiber Optics**

Remapping fiber optics have been widely used in the MS-STIL [8,16]. The basic principle of remapping fiber optics is total reflection of light, which occurs when a propagating light wave...
strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal of the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the light wave cannot pass through and is entirely reflected. The critical angle is the angle of incidence above which the total reflection of light occurs. Based on this principle, the microlens array can be used to non-uniformly sample data from the image plane, and the remapping fiber optics can be used to remap this image plane to the photocathode of the two streak tubes using scheduled arrangement rules. In this structure, at every focus point of the microlens array, there is a fiber. But the back-end of the remapping fiber optics is segmented into two parts, and every part is coupled to a photocathode of a streak tube. The fibers on the remapping fiber optics needs to meet a constraint condition. There is a spatial gap between every two adjacent lines, which is similar to that in [8]. The arrangement pattern of fibers will influence the method of image reconstruction, and the number of fibers will influence the number of available pixels of the reconstructed image. To achieve the optimal utilization rate of light energy, the structure parameters of the receiving optical system, which contains the receiving optical lens, microlens array, and remapping fiber optics needs to meet a constraint condition.

The schematic of the receiving optical system is shown in Fig. 3. In this figure, \( R \) is the radius of the receiving optical lens; \( F \) is the focal length of the receiving optical lens; \( r \) is the radius of the microlens; \( f \) is the focal length of the microlens; \( h \) is the vertical distance between the optical axis of the microlens and the optical axis of the receiving optical lens; \( d_{in} \) is the internal diameter of the fiber; and \( d_{ex} \) is the external diameter of the fiber. According to the geometrical relationship in Fig. 3, when the microlens in Fig. 3 is positioned at one of the six positions (P1–P6) in Fig. 2—and only if the six beams (L1–L6) in Fig. 3 can strike into the fiber—then, in theory, can all of the laser energy received by the microlens array be entirely transmitted into the corresponding fibers. The position and angle of the incident laser beam in the front-end of the fiber are shown in Table 1, where \( r_0 \) is the distance between the incident point of the laser beam and the center of the fiber, and \( \theta \) is the angle of the incident laser beam with respect to the normal of the surface.

**D. Streak Tube**

The basic imaging process [9,16] of the streak tube is as follows. The laser pulse signal is focused on the photocathode of the streak tube, and then the photocathode will transmit electrons. The instantaneous transmitting density of electrons is proportional to that of photons. Therefore, the electrical pulse is a duplicate of the laser pulse in the space-time structure.

When the electrical pulse goes through the sweep system, it will be unfolded along the vertical direction of the phosphor screen as the sweep voltage linearly changes in the sweep system. Therefore, the transformation from temporal signal to spatial signal is realized; the specific process is shown in Fig. 4(b). The target edges with different distances from the target to the detector have different vertical positions on the phosphor screen. Range information can be extracted by utilizing these differences in vertical positions, and intensity information can also be obtained from the stripe image, which is shown in Fig. 4(c). The horizontal direction describes spatial information and the vertical direction describes temporal information. The final range image and intensity image can be obtained by an effective reconstruction algorithm.

In the ideal condition without various internal noises, the working process of a streak tube can be approximately represented by

\[
S(x,y) = r_s \int P_s(x,y - t \cdot v_s, t) dt,
\]

where \( S(x,y) \) is the stripe image of the streak tube; \( r_s \) is the electro-optical conversion efficiency of the phosphor screen; \( P_s(x,y,t) \) is the space-time structure of the electrical signal transmitted by the photocathode; and \( v_s \) is the scanning speed of light spot on the phosphor screen, which is determined by the slope of the sweep voltage.

Fig. 4(a) shows that the DOF of the range image refers to the range between the maximum detectable range and the minimum detectable range, which also can be called the range gate. In the streak tube laser imaging system, the DOF is also equal to the minimum temporal resolution multiplied by the total number of time bins. When the temporal resolution remains unchanged, increasing the total number of time bins is the

---

**Table 1. Position and Angle of Incident Light**

<table>
<thead>
<tr>
<th>Beam</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>L5</th>
<th>L6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_0/\mu m )</td>
<td>((R-b-r)f/F)</td>
<td>((R-b+r)f/F)</td>
<td>((b+r)f/F)</td>
<td>((b-r)f/F)</td>
<td>((R+b+r)f/F)</td>
<td>((R+b-r)f/F)</td>
</tr>
<tr>
<td>( \tan \theta )</td>
<td>( r/(f + R-h-r) )</td>
<td>( r/(f + R-h+r) )</td>
<td>( r/(f + b+r) )</td>
<td>( r/(f + h-r) )</td>
<td>( r/(f + R-h+r) )</td>
<td>( r/(f + R+h-r) )</td>
</tr>
</tbody>
</table>
Fig. 4. Basic principle of streak tube. (a) Illumination model, (b) Streak tube model, and (c) Phosphor screen model.

equivalent of increasing the DOF. However, the total number of time bins of the streak tube is very limited and is determined by the number of pixels in the CCD [25]. In general, the range gate is just several tens of centimeters for a streak tube with a temporal resolution of ps level. Therefore, the streak tube laser imaging system needs to use a range gate technique and time delay device of trigger signal to realize long-distance detection. In the structure proposed in this paper, the back-end of the remapping fiber optics is segmented into two parts, and every part is coupled to the photocathode of a streak tube, which leads to the realization of the operation mode of the two streak tubes. Compared with the operation mode of a single streak tube, the operation mode of two streak tubes increases the vertical scope corresponding to every time-resolved channel on the phosphor screen—the equivalent of increasing the total number of time bins. Therefore, the DOF of this system is increased.

E. Operation Time Sequence

The MS-STIL is a complex synthetic system, which contains several subsystems. Only if the different subsystems cooperate with each other can the entire system successfully achieve the imaging function. The computer is used to control the operation time sequence of the entire system, and the different subsystems need to begin to work or stop working at different times. The actual operation time sequence of this system is shown in Fig. 5.

In Fig. 5, \( t_1 \) is the delayed time of the range gate; \( t_2 \) is the delayed time of the transmitting laser; \( t_3 \) is the delayed time of the photoelectric shutter of the streak tube; \( t_4 \) is the delayed time of the beginning work of CCD; \( t_5 \) is the delayed time of the ending work of CCD; and \( t_6 \) is the integral time of the CCD.

F. Image Construction

Figure 4(a) shows that the image collected by the streak tube is a stripe image not a real image. The final range image and the intensity image can be obtained from the stripe image through an effective image reconstruction algorithm [31]. In general, the process of image reconstruction can be divided into image improvement and feature extraction [14]. The image improvement can be used to suppress noise, improve the signal-to-noise ratio, and reduce distortion. The feature extraction can be used to extract range and intensity data from the stripe image. Before the image reconstruction is carried out, the initial position of the laser spot needs to be calibrated. The initial position value of the laser spot of every time-resolved channel on the phosphor screen can be obtained by static imaging of the streak tube without supplying sweep voltage. Then, the temporal profile can be rendered by supplying sweep voltage and taking the position of peak value of every time-resolved region as the final position value. The final range data of every time-resolved channel is proportional to the corresponding final position value subtracted by the corresponding initial position value, and the intensity data can be obtained by taking the magnitude value. It is worth mentioning that all the range data obtained by the above process are relative range data. The absolute range data are equal to the relative range data added to the delayed range of the range gate.

G. Range Equation of Laser Detection

The performance of the laser detection system mainly depends on its range equation. The range equation is widely used as an analytical tool for computing the reflected power of a laser detection system. To simplify this problem, we need to assume that laser transmission in the atmosphere conforms to the principle of geometrical optics; the atmosphere is homogeneous and isotropic; the target object belongs to Lambert radiators; the distribution of laser energy on the surface of the target objects is uniform; and there is not any noise and interference in the system. The laser detection range equation can be written as [32]

\[
P_r = \frac{4\pi r_d^2 \rho_s (dA) P_t}{L^2 \theta_i^2 (\theta_s, L)}
\]

where \( r_d \) is the transmission efficiency of the receiving optical lens and the quantum efficiency of the detector; \( r_d \) is the atmosphere transmission factor; \( R \) is the radius of the receiving optical lens; \( \rho_s \) is the target surface reflectivity; \( dA \) is the receiving area of the reflected laser; \( P_t \) is the laser transmitting power; \( L \) is the range length between detector and target; \( \theta_s \) is the angular divergence of the transmitting laser beam; \( \theta_i \) is the angular dispersion of the target surface; and \( P_r \) is the output power of the detector.
Assuming that the illuminating area of the laser is not smaller than the area of the receiving area of the reflected laser, and the receiving area is perpendicular to the optical axis of the receiving optical lens, then \( dA \) can be written as [32]
\[
dA = (\Delta/F \times L)^2,
\]
where \( \Delta \) is the physical size of the detector and \( F \) is the focal length of the receiving optical lens.

**H. Reflected Laser Signal**

In general, the laser pulse waveform is described by the parabolic model or the Gaussian model. However, there is a difference between these two models and the real laser pulse model. Here, one of the key issues is how to describe the laser pulse waveform. In this paper, we have solved the problem by using the hybrid model in such a way that the first half-pulse of the Gaussian model is combined with the second half-pulse of the parabolic model. Then, the output signal of the detector can be written as [32]
\[
P_i(t) = \frac{4\tau_0^2 r_0^2}{T_0^2} \frac{r_i(dA)}{\Theta_0(\theta,t)} \cdot H\left(t - \frac{2t_1}{c}\right) \cdot P_0 + N(t),
\]
where \( P_i(t) \) is the output electrical signal of the detector; \( P_0 \) is the peak power of the illuminating laser pulse; and \( N(t) \) is the noise signal, which mainly contains photon counting noise, laser speckle, thermal noise, and background noise. Reference [32] explains in detail how to represent these noises using mathematical language. \( H(t) \) is the waveform of the illuminating laser pulse; it can be written as [32]
\[
H(t) = \left(1 - \frac{4t^2}{p_w^2}\right) \text{rect}\left(\frac{2t + p_w/2}{p_w}\right) + e^{\frac{2t}{\sigma_w}} \text{rect}\left(\frac{t - 5\sigma_w/2}{5\sigma_w}\right),
\]
where \( \sigma_w \) and \( p_w \) are two pulse shape coefficients, which can determine the steepness of an illuminating laser pulse waveform.

In order to obtain a signal, we must assume that the receiving area of each detector unit is perpendicular to the optical axis of the receiving optical lens. However, it is very difficult to meet this requirement in the real application. Therefore, the target surface shape corresponding to each detector unit needs to be considered. The method of finite element analysis can be used to solve this question [32]. We can divide the receiving area of each detector unit into a finite small area and assume that each small area meets the above imaging requirement. In this paper, each small area refers to a pixel of input image. Then the output signal of each detector unit can be written as [32]
\[
P_i(t) = \sum_i P_i(t) + N(t),
\]
where \( P_i(t) \) is the receiving signal corresponding to the \( i \)th small area in the receiving area of each detector unit.

Assuming that in the streak tube the output electrical signal of the photocathode meets a 2D Gaussian distribution, then the space-time structure can be written as
\[
P_i(x, y, t) = P_i(t) \cdot G(x, y),
\]
where \( G(x, y) \) is the spatial structure of the electrical signal, which is a 2D Gaussian distribution in this paper.

**3. EXPERIMENTS**

The mathematical model of the entire streak tube laser imaging system is established according to Eqs. (2)–(8). In order to analyze the feasibility and the performance of the proposed imaging system, three simulated contrast experiments were organized. The actual structure parameters of the proposed imaging system are shown in Table 2. The regular MS-STIL is used as a contrast object in the experiment, and it uses a uniform sampling pattern and operation mode of a single streak tube. The regular imaging system also contains remapping fiber optics. The type and the number of fibers in the remapping fiber optics of the regular imaging system are the same as those of the proposed imaging system. But, in the front of the remapping fiber optics of the regular imaging system, there is no microlens array to collect the reflected laser energy [8,16]. The remapping fiber optics of the proposed imaging system contain \( 64 \times 64 \) fibers, and its back-end is divided into two parts. Every part contains \( 8 \times 256 \) fibers. The remapping fiber optics of the regular imaging system also contain \( 64 \times 64 \) fibers, and its back-end contains \( 16 \times 256 \) fibers. The other parameters used in the regular imaging system are the same as those of the proposed imaging system.

In Section 2.C, it is noted that in order to achieve an optimal utilization rate of light energy, the structure parameters of the receiving optical system—which contains a receiving optical lens, microlens array, and remapping fiber optics—needs to meet a constraint condition. The actual values of Table 1 are obtained using the values in Table 2, and they are shown in Table 3. The fibers used in this paper have the internal diameter of \( 120 \mu m \), an external diameter of \( 125 \mu m \), and a

<table>
<thead>
<tr>
<th>Table 2. Parameter Values Used in the Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Parameters</strong></td>
</tr>
<tr>
<td>Power of laser ( (P_i) )</td>
</tr>
<tr>
<td>Wavelength of laser ( (\lambda) )</td>
</tr>
<tr>
<td>Width of laser pulse ( (\tau_0) )</td>
</tr>
<tr>
<td>Pulse shape coefficient ( (\sigma_w/p_w) )</td>
</tr>
<tr>
<td>Angular divergence of laser ( (\theta_i) )</td>
</tr>
<tr>
<td>Aperture radius ( (R) )</td>
</tr>
<tr>
<td>Focal length ( (F) )</td>
</tr>
<tr>
<td>Radius of microlens ( (r) )</td>
</tr>
<tr>
<td>Focal length of microlens ( (f) )</td>
</tr>
<tr>
<td>Ring number ( (n_1/n_2/n_3) )</td>
</tr>
</tbody>
</table>
numerical aperture of 0.5. Toray Industries has a fiber product that meets this requirement. In Table 3, we find that all of the distances between the laser beam incident positions and the centers of fibers are smaller than 60 μm, and all of the incident angles of the laser beam on the cross profile of fiber with respect to the normal of the surface are smaller than 0.5. Therefore, the imaging system in this paper can achieve an optimal utilization rate of light energy.

A. Contrast Experiment on Spatial Resolution and FOV

In order to verify the advantages of the proposed imaging system concerning spatial resolution and FOV, a contrast experiment was carried out. In the process of the experiment, the tank image shown in Fig. 6(a) was used as the initial range image, and the image shown in Fig. 6(b) was used as the initial intensity image. The size of this tank is 8.0 m × 3.7 m × 2.8 m, and it comes from Princeton Shape Benchmark [33]. The tank was imaged by the regular system and the proposed system at a distance of 1000 m, respectively. The final imaging results are shown in Fig. 6.

Figures 6(c1) and 6(c2) are two stripe images generated by the proposed imaging system. In Fig. 6(c1), we find that the stripe’s brightness suddenly darkens in a certain position. This is because there are three kinds of microlenses with different apertures in the microlens array. Under the condition of the same reflected power density, the microlens with the maximum aperture will have the strongest reflected energy. Figure 6(f) is the stripe image generated by the regular imaging system, and there is just a slight change in the stripe’s brightness due to the changing of the target surface reflectivity. Figures 6(d) and 6(e) are the range image and intensity image, respectively, which are obtained by image reconstruction of the peak detection method.

<table>
<thead>
<tr>
<th>Laser Beams</th>
<th>r₀/μm</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>L5</th>
<th>L6</th>
</tr>
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<tbody>
<tr>
<td>P1</td>
<td>46.7</td>
<td>46.8</td>
<td>0.14</td>
<td>0.02</td>
<td>47.0</td>
<td>46.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tan θ</td>
<td>0.15</td>
<td>0.02</td>
<td>0.08</td>
<td>0.08</td>
<td>0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>P2</td>
<td>43.6</td>
<td>43.7</td>
<td>3.29</td>
<td>3.17</td>
<td>50.2</td>
<td>50.0</td>
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<tr>
<td></td>
<td>tan θ</td>
<td>0.14</td>
<td>0.03</td>
<td>0.08</td>
<td>0.09</td>
<td>0.02</td>
<td>0.15</td>
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<td>P3</td>
<td>43.3</td>
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<td>50.5</td>
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<tr>
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<td>0.16</td>
<td>0.17</td>
<td>0.10</td>
<td>0.23</td>
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<tr>
<td>P4</td>
<td>39.6</td>
<td>39.9</td>
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<td>7.01</td>
<td>54.1</td>
<td>53.9</td>
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<td>0.11</td>
<td>0.16</td>
<td>0.18</td>
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<td>P6</td>
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<td>34.8</td>
<td>12.5</td>
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Fig. 6. Experiment result: (a) initial range image, (b) initial intensity image, (c) stripe image of this work, (d) range image of this work, (e) intensity image of this work, (f) stripe image of previous work, (g) range image of previous work, and (h) intensity image of previous work.
based on Figs. 6(c1) and 6(c2). Compared with the intensity image, the range image has a better imaging quality. The width of the imaging laser pulse is very narrow and the power of the imaging laser pulse is very strong, which give the range image a good range precision. But because the coherence of the imaging laser is very strong, there is a strong laser speckle noise in the laser’s reflected signal, which causes bad precision in the intensity image. In the intensity image, we can clearly see that the spatial resolution decreases stepwise from the center to the edge of the FOV. When reconstructing the intensity image, because of the existence of the non-uniform sampling pattern, different sampling areas in the image plane have a big difference in image brightness; therefore, a ratio factor is used to adjust the image brightness of different sampling areas. Figures 6(g) and 6(h) are the range image and intensity image, respectively, which are obtained by image reconstruction of the peak detection method based on Fig. 6(f). In these two images, the spatial resolution is constant. Figure 6 proves that the proposed imaging system has a wider FOV under the premise of the same spatial resolution in the center of the FOV. In the proposed imaging system, the minimum aperture in the microlens is 125 μm. The ratio of the number of the three different kinds of microlenses is 20:12:8, and the total number of microlenses is 64 × 64. The sampling area of the proposed imaging system (its sampling area is 19 mm × 19 mm) is 5.6 times bigger than that of the regular imaging system (its sampling area is 8 mm × 8 mm). Therefore, we can conclude that the proposed imaging system possesses a property of wider FOV under high center spatial resolution, which relieves the conflict between high spatial resolution and wide FOV.

B. Contrast Experiment on Temporal Resolution and DOF

In order to verify the advantages of the proposed imaging system concerning temporal resolution and DOF, a contrast experiment was carried out. As shown in Fig. 7, the object with a special design was used as the desired target. Figure 7(a) was used as the initial range image, and Fig. 7(b) was used as the initial intensity image. There are 25 cylinders with different depths in range image. Their depth values, whose units are m, are shown in the corresponding positions of the range image. Furthermore, every cylinder has a numerical symbol, which is shown in the corresponding positions of intensity image. The target was imaged by the regular system and the proposed system at a distance of 1000 m, respectively. The final imaging results are shown in Fig. 7.

![Fig. 7. Experiment result: (a) initial range image, (b) initial intensity image, (c) stripe image of this work, (d) range image of this work, (e) intensity image of this work, (f) stripe image of previous work, (g) range image of previous work, and (h) intensity image of previous work.](image-url)
Figures 7(c1) and 7(c2) are two stripe images generated by the proposed imaging system. In these two images, we find that the stripe’s brightness suddenly changes at certain points. Figure 7(f) is the stripe image generated by the regular imaging system. Figures 7(d) and 7(e) are the range image and intensity image, which are obtained by image reconstruction of the peak detection method based on Figs. 7(c1) and 7(c2). In the range image and intensity image, we find that the spatial resolution decreases stepwise from the center to the edge of the FOV. In the intensity image, we find that there are four circular areas with low surface reflectivity in positions 10, 14, 18, and 22. The reason for this phenomenon is that the depths of these four cylinders are 13, -15, -13, and 15, and they are beyond the scope of the range gate (-12.8, 12.8). Therefore, in the imaging process of the proposed imaging system, these four positions cannot receive any reflected laser energy and can receive only background noise. Thus, the range value of every pixel in these positions is random, and the intensity values are very small. Figures 7(g) and 7(h) are the range image and intensity image, which are obtained by image reconstruction of the peak detection method based on Fig. 7(f). We find that the FOV of the regular imaging system is smaller than that of the proposed imaging system. And in the regular imaging system in positions 2, 4, 6, and 8, there is also a phenomenon in which the depths of cylinders are beyond the scope of the range gate (-6.4, 6.4). We also find that the vertical scope corresponding to every time-resolved channel in Fig. 7(c) is two times bigger than that in Fig. 7(f), but the number of stripes of every stripe image falls by half. Therefore, we conclude that the proposed imaging system possesses a property of deeper DOV under the high temporal resolution (0.2 m/pixel), which resolves the conflict between high temporal resolution and deep DOV.

C. Contrast Experiment on Detectable Range

In order to verify the advantages of the proposed imaging system concerning detectable range, a contrast experiment was carried out. The objects in this experiment are vertical plane, inclined plane, and step plane. These three targets were imaged by the regular system and the proposed system at a distance of 1000 m, respectively. The final detection results are shown in Fig. 8, and all of the results do not contain any noise. The blue curve is the reflected laser signal of the microlens with the medium aperture; the red curve is the reflected laser signal of the microlens with the minimum aperture; and the black curve is the reflected laser signal of the microlens with the maximum aperture.

The detection result of the vertical plane is shown in Fig. 8(a). We find that the strength of the reflected laser signal increases with the increase of the aperture in the microlens. The detection result of the inclined plane is shown in Fig. 8(b). We find that the phenomenon is similar to that in Fig. 8(a). Furthermore, we also find that the strength of the reflected pulse signal is weaker, and the width of reflected pulse signal is broader than that in Fig. 8(a). This is because the total travel time corresponding to every finite small area on the surface of the inclined plane is different. The detection result of the step plane is shown in Fig. 8(c). We also find that the phenomenon is similar to that in Fig. 8(a). Furthermore, we also find that the strength of the reflected pulse signal is weaker, and the reflected pulse signal is divided into two pluses. This is because the total travel time corresponding to every plane on the surface of the step plane is different, and the difference in travel time is enough to divide the pulse signal into two pulses. Because the aperture of the fiber of the regular imaging system is similar to the minimum aperture of the microlens of the proposed imaging system, the detectable range ability of the regular system is similar to the minimum detectable range ability of the proposed system. That means the synthetic detectable range ability of the proposed system is better than that of the regular system. Therefore, we conclude that no matter the target shape, the detectable range ability of the proposed imaging system increases from the center to the edge of the FOV, and it is better than that of the regular imaging system. We can divide the FOV into three parts. The first part corresponding to the microlens with the minimum aperture is used to make precise target recognition. The second part corresponding to the microlens with the medium aperture is used to determine whether the target needs to be recognized further. The third part corresponding to the microlens with the maximum aperture is used to search the target in a large area.

4. DISCUSSIONS

It is well known that the MTF is a good method to evaluate an imaging system. When an imaging system can be divided into many subsystems, its total MTF is equal to the product of the
MTFs of all subsystems. The streak tube laser imaging system is a special imaging system, and it has two working modes: static working mode and dynamic working mode. Therefore, there are three kinds of MTF in the imaging system: temporal modulation transfer function (TMTF), static spatial modulation transfer function (SSMTF), and dynamic spatial modulation transfer function (DSMTF) [34]. These three kinds of MTF can be obtained by the Fourier transform of their corresponding point spread functions (PSF). Compared with the regular streak tube imaging system, a microlens array and a remapping fiber optics are introduced into the new imaging system. Therefore, we need to analyze the effect of these two new components on range resolution and spatial resolution using the MTF.

First, we analyze the TMTF of the microlens array and remapping fiber optics. In theory, there is no effect from the microlens array and remapping fiber optics on the reflected laser pulse in the temporal domain. However, due to dispersion, when the laser pulse passes through the fiber, the width of the reflected laser pulse will be broadened. But the experiment proved that when the fiber length is less than 1 m, the change of the pulsed width is less than 1 ps [35]. In a real application, the length of the fiber in our remapping fiber optics is far less than 1 m. Therefore, the cut-off frequency of the TMTF of the remapping fiber optics is very high, which is far bigger than the desired temporal frequency. Therefore, the microlens array and remapping fiber optics hardly affect the reflected laser pulse in the temporal domain.

Second, we analyze the DSMTF of the microlens array and remapping fiber optics. Just as in the previous analysis, these two new components hardly affect the reflected laser pulse in the temporal domain. Therefore, the cut-off frequency of the DSMTF of the remapping fiber optics is also far bigger than the desired temporal frequency. Therefore, we conclude that compared with the regular imaging system the new microlens array and remapping fiber optics hardly affect the range resolution of the entire imaging system.

Third, we analyze the SSMTF of the microlens array and remapping fiber optics. In theory, the microlens array is a kind of low pass filter in the spatial domain. The cutoff spatial resolution of the entire imaging system is equal to the spatial resolution of the microlens array. As there are three different spatial resolutions in the microlens array, the microlens array can produce three different effects on the total SSMTF of the entire system. The remapping fiber optics do not affect the total SSMTF. Therefore, we conclude that compared with the regular imaging system the new microlens array and remapping fiber optics will affect the spatial resolution of the entire imaging system. But variable spatial resolution is one of the contributions in this paper that can relieve the conflict between high spatial resolution and wide FOV and increase the detectable range of the system.

5. CONCLUSIONS
This paper presents a new non-scanning streak tube laser imaging system. This system can realize a non-uniform sampling pattern using a microlens array so that it relieves the conflict between high spatial resolution and wide FOV and also increases the detectable range of the system. This system can realize the operation mode of two streak tubes using remapping fiber optics so that it increases the vertical scope corresponding to every time-resolved channel on the phosphor screen and relieves the conflict between high temporal resolution and deep DOV. The mathematical model of the entire streak tube laser imaging system is established based on the range equation of laser detection. The structure parameters of the receiving optical system are optimized in order to achieve an optimal utilization rate of light energy. The effect of the microlens array and remapping fiber optics on temporal resolution and range resolution is analyzed by the MTF, and the result shows that the new microlens array and remapping fiber optics hardly affect the range resolution of the entire imaging system. But, they will affect spatial resolution of the entire imaging system. Three simulated contrast experiments are organized, and the final experiment results demonstrate that the imaging system proposed in this paper possesses properties of higher spatial resolution, wider FOV, higher temporal resolution, deeper DOF, and a larger detectable range.

Funding. National Natural Science Foundation of China (NSFC) (61275018); International Science and Technology Cooperation Project (2015DFR10830); China Scholarship Council (CSC).

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