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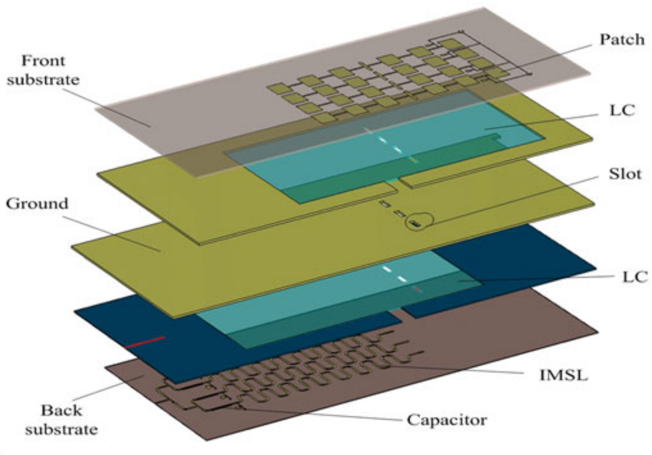

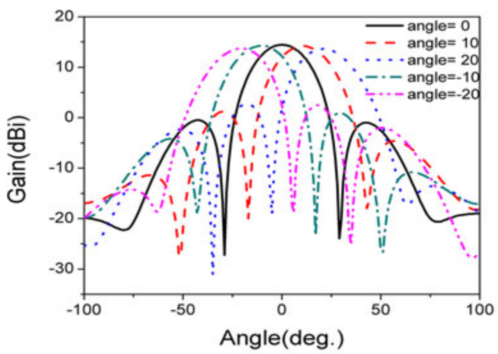

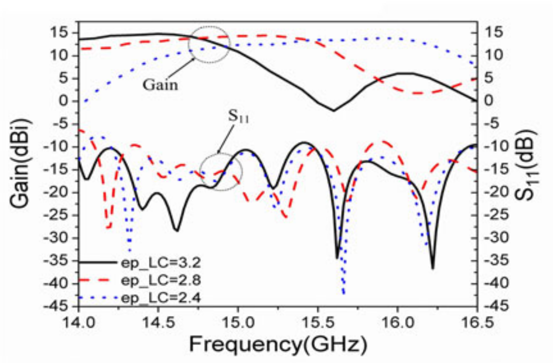

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A Frequency and Pattern Reconfigurable Antenna Array Based on Liquid Crystal Technology

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Abstract: A reconfigurable antenna array based on liquid crystal (LC) technology is proposed, which can dynamically tune operation frequency and achieve beam steering. The antenna element is composed of two parts: a microstrip patch array and a phase shifter using the inverted microstrip line (IMSL). The LC substrate is used to support the patch array for controlling its resonance frequency, while the LC-based IMSL phase shifter is adopted to tune the transmission phase by changing the effective permittivity of the LC. In order to verify the reconfigurable characteristics, the antenna array consisting of 1×4 elements are designed and numerically investigated. Simulation results show that this antenna can realize beam steering with a scanning angle range of (–20°, 20°), while its operation frequency can be actively tuned between 14.5 and 16.4 GHz.

Index Terms: Liquid crystal, reconfigurable antenna, frequency-agile, beam steering.

1. Introduction

With the rapid development of modern electronic technology, a great variety of applications must coexist in current antenna systems, which has triggered the demand of multi-functional antennas. Aiming at this target, reconfigurable technology has been presented and intensively investigated in the antenna fields. There are two kinds of approaches to construct the reconfigurable antenna. One is to adopt discrete elements, such as the varactor [1]–[3] or PIN diodes [4] and the MEMS switch [5]. The other is to use tunable materials [6]–[11], including ferro-electric film, grapheme, and liquid crystal (LC). Among them, the diodes are often utilized in applications below 10 GHz owing to the increased effect of their parasitic resistances in the higher frequency. As a low-cost and low-loss material, LC is very suitable for applications above 10 GHz, which can continuously tune the dielectric properties of the material by applying a quasi-static bias voltage [12]–[14]. The material characterization of LC has been extensively investigated in microwave and millimeter-wave frequencies, which have experimentally verified the dynamical control of the permittivity and their low tangent loss.

So far, there are few studies on the actual utilization of LC in microwave applications. Parts of these works have focused on the implementation of LC in electrically tunable phase shifters

[15] and delay microstrip lines [16]. Some researchers have concentrated on the design of LC-based antennas. In [17], LC has been utilized as the substrate for a patch antenna, which can tune the operation frequency antenna by changing bias voltage. The phase array antenna has been also reported [18], [19] to actively control the emitted beam direction by controlling the integrated LC-based phase shifter. To the best of our knowledge, the existing LC technology has only realized the active control of one function (operation frequency or beam direction) for the designed antenna, which cannot simultaneously achieve the reconfiguration of the multi-functions in one antenna.

In this work, a LC-based reconfigurable antenna array is proposed to simultaneously tune the operation frequency and beam direction. The series-fed patch array antenna is modified in a way that LC is used as a tunable substrate to change its resonance frequency. A further modification process is to integrate the LC-based phase shifter with the patch array for realizing continuous phase adjustment. Finally, the designed antenna array consisting of 1 × 4 patch array has been numerically verified to possess both frequency-agile and beam-steering capabilities.

2. Principle

The LC used in this work is in the nematic phase, and it can exhibit different dielectric characteristics depending on how an external static electric field is applied to the LC molecules owing to anisotropy. For the unbiased state, the LC shows the minimum permittivity represented by $\varepsilon_{\mathrm{r,LC}\perp}$. That means the orientation of LC molecules is perpendicular. Intruding the bias voltage would orient the LC molecules, which causes a variation in the effective permittivity of the LC. When the voltage is further increased, most of the LC molecules would orient in parallel with the static field, hence the maximum value of $\varepsilon_{\mathrm{r,eff}}$ is obtained, which is indicated by $\varepsilon_{\mathrm{r,LC}\parallel}$. Based on the above operation mechanism, the LC can be utilized as tunable substrate. When it is applied in the patch antenna, the LC substrate is expected to tune the resonance frequency of the microstrip patch as the varying permittivity would change the guide wavelength. In addition, the phase constant of the guided wave is roughly equivalent to $\beta = \mathrm{k}\sqrt{\mu_r \varepsilon_{rLC}}$, and therefore, tuning permittivity would also result in a different transmission phase. For the phase arrayed antenna, the phase difference between the two adjacent radiating elements can be expressed as $\Delta\phi = -\mathrm{p}\beta = -\mathrm{kp}\sqrt{\mu_r \varepsilon_{rLC}}$, where p is the distance between adjacent elements. The maximum phase tuning range is about ($\mathrm{kp}\sqrt{\mu_r \varepsilon_{rLC\parallel}} \sim \mathrm{kp}\sqrt{\mu_r \varepsilon_{rLC\perp}}$). When using LC substrate to produce a gradient phase distribution for the antenna elements, the beam steering can be achieved. In this work, the type of LC is chosen as GT3-23001 that is manufactured by Merck, and its parameters are $\varepsilon_{\mathrm{r,LC}\parallel} = 3.2$, $\varepsilon_{\mathrm{r,LC}\perp} = 2.4$, $\tan\delta_{\parallel} = 0.002$, and $\tan\delta_{\perp} = 0.006$ [20].

3. LC-Based Reconfigurable Antenna Design

3.1 LC-Based Patch Antenna Design

Fig. 1 shows geometrical model of the series-fed patch array using LC substrate and the inspiration of the structure comes from [21]. This antenna is designed to operate at Ku-band, and its resonance frequency could be dynamically controlled by tuning the effective permittivity of the LC substrate. The patch array is made of a series of six rectangular metallic patches etched on a bottom side of Rogers RT5880 with permittivity of $\varepsilon_{\mathrm{r}} = 2.2$, and it is fed through slot-coupling technique at its center. The feeding line is fabricated on the upper side of the bottom substrate that is 0.127 mm-thick Rogers RT5880. The metallic ground plane is employed between the patch array and feeding line, which includes a slot to support electromagnetic aperture coupling. In order to tune the operation frequency of the antenna, two cavities filled by the LC material is constructed. One cavity with thickness of 0.5 mm is inserted between the top substrate and the ground plane, while the other cavity that is 0.254 mm-thick is placed between the ground and the bottom substrate.

Numerical simulation is carried out to investigate the frequency-agile characteristic of the designed antenna by using a commercial software CST Microwave Studio 2014. It is seen in Fig. 2

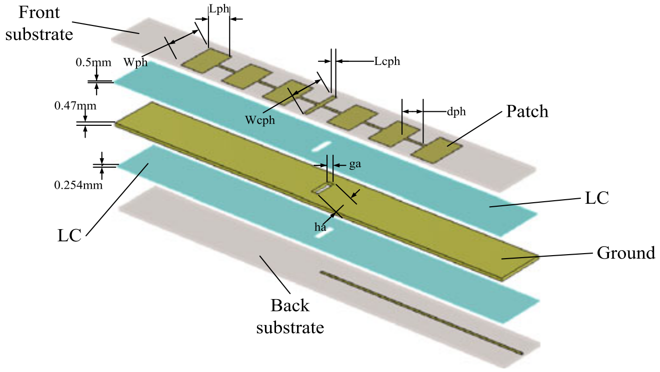

Fig. 1. Geometrical model of the series-fed patch array using LC substrate. Dimensions of the antenna (mm): Wcph = 8 mm, Lcph = 1 mm, Wph = 8 mm, Lph = 5.5 mm, dph = 5.5 mm, ha = 5 mm, ga = 1.5 mm.

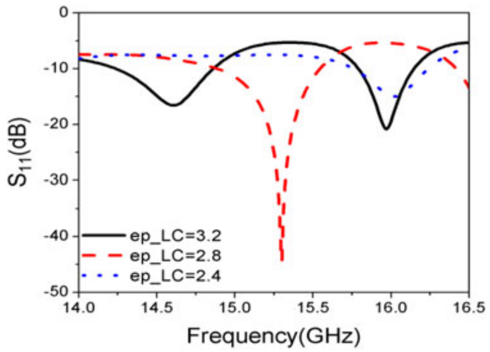

Fig. 2. S11 of the proposed LC-based antenna for different permittivities.

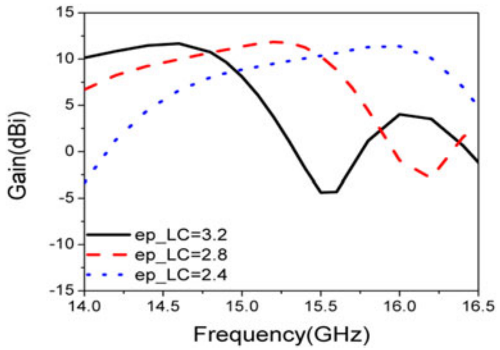

Fig. 3. Frequency response of the antenna gain for different permittivities.

that the designed antenna, respectively, resonates at 16.1 GHz, 15.3 GHz, and 14.5 GHz when the permittivity of the LC substrate is set to be 2.4, 2.8, and 3.2. Fig. 3 depicts frequency response of the antenna gain for different permittivities. As it shows, the operation frequency for the peak gain is also shifted from 16.1 GHz to 14.5 GHz as the value of permittivity is varied from 2.4 to 3.2, and the peak gain of this antenna is almost identical at these three cases, which is about 12 dBi. In addition, it is found that there is almost no frequency shift between the positions for the resonance frequency of S11 and the peak gain at each permittivity.

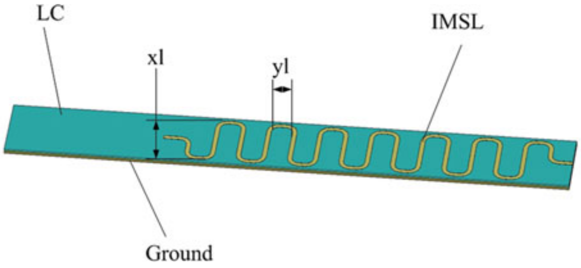

Fig. 4. Schematic model of the LC-based phase shifter structure.

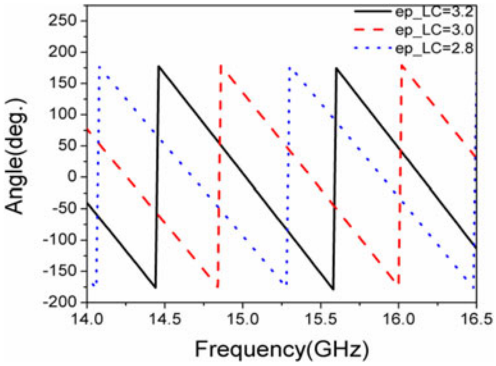

Fig. 5. Phase response of the designed phase shifter for different permittivities.

3.2 LC-Based Phase Shifter Design

The schematic model of the LC-based phase shifter is shown in Fig. 4. The LC is utilized as the substrate for the microstrip line. When changing the bias voltage that applied on the LC, the effective permittivity of the LC substrate will change correspondingly, producing the phase shifting of the guided wave signal through the microstrip line. In order to achieve large phase tuning range, an inverted microstrip line (IMSL) structure is adopted. As Fig. 4 shows, the parameters of the IMSL structure is designed as follows: $x1 = 9$ mm and $y1 = 3$ mm, and the thickness of the LC layer is about 0.25 mm. The simulation result for the phase response of the designed phase shifter is given in Fig. 5. It is seen that the phase tuning range of 185° is obtained between 15.3 GHz and 14.5 GHz as the permittivity is varied from 2.8 to 3.2. When using this phase shifter to construct the antenna array along x direction, the gradient phase distribution could, be obtained, and the antenna is expected to achieve beam steering.

3.3 Design of a Frequency and Pattern Reconfigurable Antenna Array

Fig. 6 shows the final model of the frequency and pattern reconfigurable antenna array. The series-fed patch array and the phase shifter using IMSL are integrated to construct the antenna element. Two LC layers are utilized to tune the antenna frequency and radiation pattern, respectively. One LC layer is placed between the patch array and the ground plane, and the other layer is inserted between the ground plane and the phase shifter. The final antenna configuration is composed of 1×4 antenna elements, and it is excited by the parallel feeding network. In order to produce the desired phase shift between the neighboring antenna element, each phase shifter is required to be independently controlled. The interdigital capacitor is utilized in each branch of an one-to-four power divider. Its insertion loss is simulated to be less than 0.5 dB between 14. 2 GHz and 16.1 GHz where S11 is less than -20 dB. Therefore, the employing interdigital capacitor has almost no influence in

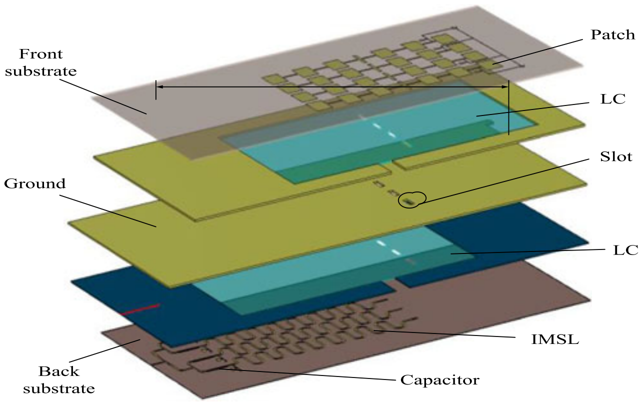

Fig. 6. Schematic model of the proposed reconfigurable antenna array.

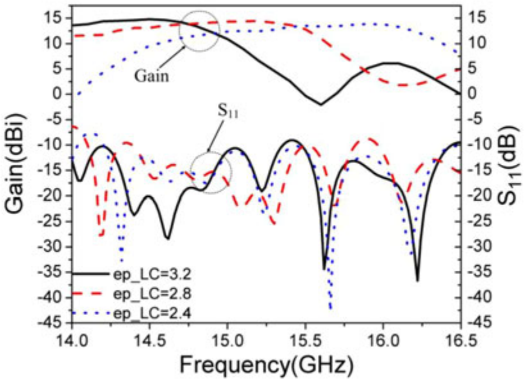

Fig. 7. Gain and S11 of the reconfigurable antenna array with different permittivities.

TABLE 1

Permittivities of LC for Each Antenna Element at the Scanning Angle of −20°, −10°, 0°, 10°, and 20°

Scanning angle	$\varepsilon_{\text{element1}}$	$\varepsilon_{\text{element2}}$	$\varepsilon_{\text{element3}}$	$\varepsilon_{\text{element4}}$
−20°	2.8	2.93	3.07	3.2
−10°	2.8	2.87	2.93	3.0
0°	2.8	2.8	2.8	2.8
10°	3.0	2.93	2.87	2.8
20°	3.2	3.07	2.93	2.8

the transmission of the RF signal at the frequency region of interest but can effectively isolate the DC signal. Therefore, the bias voltage can be independently applied to each phase shifter.

Fig. 7 shows the reflection coefficient and gain of this reconfigurable antenna array with different permittivities. It is seen that the resonance frequency for the peak gain can be continuously tuned from 14.5 GHz to 16.1 GHz when the permittivity is varied from 3.2 to 2.4. The peak gain is larger than 12 dBi and the corresponding S11 is less than −10 dB for the above three cases. In order

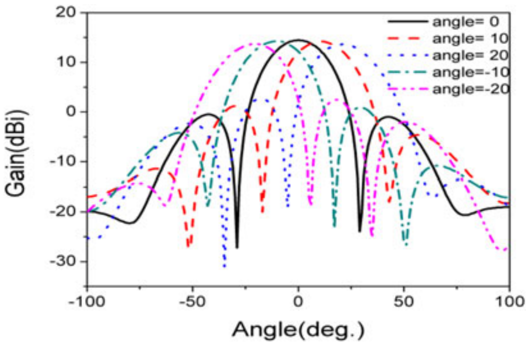

Fig. 8. Beam steering performance of the reconfigurable antenna array at 14.5 GHz.

to verify the beam steering performance of the reconfigurable antenna array, the radiation patterns of the antenna array with different phase difference are investigated at the resonance frequency of 14.5 GHz. Table 1 lists the permittivities of LC for each antenna element at the scanning angle of −20°, −10°, 0°, 10°, 20°, respectively. The corresponding transmission phase difference are about −185°, −94°, 0°, 94°, 185°, respectively. Fig. 8 depicts the simulated radiation patterns of this antenna array. It is seen that the designed antenna array produces directive beams with different radiation angles at 14.5 GHz and the antenna gains all exceed 12 dBi. The radiation angles of the main lobes are directed towards −20, −10, ... , respectively. Therefore, this reconfigurable antenna array has been demonstrated to simultaneously possess the frequency and radiation reconfigurable properties.

4. Conclusion

In conclusion, we have proposed a reconfigurable antenna array using LC technology. The antenna element consists of a series-fed patch array and a IMSL phase shifter. The operation frequency of the patch array and the transmission phase of the phase shifter can be dynamically tuned by changing the permittivity of the LC substrate. The antenna array consisting of 1×4 elements are adopted to verify its reconfigurable properties. Simulation results show that the designed antenna array can dynamically change its operation frequency between 14.5 GHz and 16.4 GHz, where the beam direction can be also tuned from −20° to 20°.

The purpose to exploit the liquid crystal technology in this antenna was to obtain electronic reconfigurability, continuous tunability, and low-power biasing. This reconfigurable antenna array might be potentially in communications. For example, arrays with many elements can be fabricated with a simple and low-cost automated manufacturing technique. Such an antenna can be utilized for applications such as wireless internet, multimedia, communication, and broadcasting services from terrestrial systems and satellites to a mobile terminal.

Fabrication of the prototype antenna has been in progress. Experimental validation will be conducted once the prototype is available. Experimental results and further follow up work will be timely reported in following publications.

References

[1] T. Jiang, Z. Y. Wang, D. Li, J. N. Pan, and B. Zhang, "Low-DC voltage-controlled steering-antenna radome utilizing tunable active metamaterial," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 1, pp. 170–178, Jan. 2012.

[2] W. B. Pan, C. Huang, P. Chen, M. B. Pu, X. L. Ma, and X. G. Luo, "A beam steering horn antenna using active frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6218–6223, Dec. 2013.

[3] J. Y. Lau and S. V. Hum, "A wideband reconfigurable transmitarray element," *IEEE Trans. Antennas Propag.*, vol. 60, no. 3, pp. 1303–1311, Mar. 2012.

[4] A. F. Sheta and S. F. Mahmoud, “A widely tunable compact patch antenna,” *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 40–42, 2008.

[5] E. Erdil, K. Topalli, M. Unlu, O. A. Civil, and T. Akin, “Frequency tunable microstrip patch antenna using RF MEMS technology,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 4, pp. 1193–1196, Apr. 2007.

[6] V. Kononov, C. A. Balanis, A. C. Polycarpou, and C. R. Birtcher, “Non-uniform field modeling of ferrite-loaded cavity-backed slot antenna,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3402–3405, Oct. 2009.

[7] Y. G. Chen *et al.*, “Hybrid phase-change plasmonic crystals for active tuning of lattice resonances,” *Opt. Exp.*, vol. 21, no. 11, pp. 13691–13698, 2013.

[8] Y. G. Chen *et al.*, “Engineering the phase front of light with phase-change material based planar,” *Sci. Rep.*, vol. 5, 2015, Art. no. 8660.

[9] D. Wang *et al.*, “Switchable ultrathin quarter-wave plate in terahertz using active phase-change metasurface,” *Sci. Rep.*, vol. 5, 2015, Art. no. 15020.

[10] R. Bose and A. Sinha, “Tunable patch antenna using a liquid crystal substrate,” in *Proc. Conf. IEEE Radar*, 2008, pp. 123–128.

[11] N. Martin, P. Laurent, C. Person, P. Gelin, and F. Huret, “Patch antenna adjustable in frequency using liquid crystal,” in *Proc. 33rd Eur. Conf. Microw.*, Oct. 2003, vol. 3, pp. 1417–1420.

[12] S. Bulja, D. M. Syahkal, R. James, S. E. Day, and F. A. Fernandez, “Measurements of dielectric properties of nematic liquid crystals at millimeter wavelengths,” *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 12, pp. 3493–3501, Dec. 2010.

[13] F. Yang and J. R. Sambles, “Resonant transmission of microwaves through a narrow metallic slit,” *Phys. Rev. Lett.*, vol. 89, no. 6, Aug. 2002, Art. no. 063901.

[14] F. Yang and J. R. Sambles, “Determination of the permittivity of nematic liquid crystals in the microwave region,” *Liq. Cryst.*, vol. 30, no. 5, pp. 599–602, 2003.

[15] F. Goelden, A. Gaebler, M. Goebel, A. Manabe, S. Mueller, and R. Jacoby, “Tunable liquid crystal phase shifter for microwave frequencies,” *Electron. Lett.*, vol. 45, no. 13, pp. 686–687, 2009.

[16] S. Bulja and D. M. Syahkal, “A 2-D electronically steered phased-array antenna with $2{*}2$ elements in LC display technology,” *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 5, pp. 1297–1305, May 2012.

[17] A. C. Polycarpou, M. A. Christou, and N. C. Papanicolaou, “Tunable patch antenna printed on a biased nematic liquid crystal cell,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 4980–4987, Oct. 2014.

[18] O. H. Karabey, A. Mehmood, M. Ayluctarhan, H. Braun, M. Letz, and R. Jakoby, “Liquid crystal based phased array antenna with improved beam scanning capability,” *Electron. Lett.*, vol. 50, no. 6, pp. 426–428, 2014.

[19] G. Perez-Palomino *et al.*, “Design and demonstration of an electronically scanned reflectarray antenna at 100 GHz using multiresonant cells based on liquid crystals,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3722–3727, Aug. 2015.

[20] S. Bildik *et al.*, “Reconfigurable folded reflectarray antenna based upon liquid crystal technology,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 122–132, Jan. 2015.

[21] J. Li *et al.*, “Far-field radiation of coherent and incoherent combined Lorentz-Gaussian laser array,” *Proc. SPIE*, vol. ID666, pp. 77491Z, 2010.