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Present Development and Tendency of Laser Display Technology

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Abstract: Display devices are at the terminal of information display in interactions between humans and machines and are expanding to all aspects of people's lives in the information age. Currently, all display technologies are developing toward high-fidelity images with ultrahigh resolution, large screen, and true color to satisfy the demand for perfect visual senses. Laser display technology uses tricolor laser as the display light source and can reproduce high-fidelity images with dual high definition (geometry/color), large color gamut, and high viewing comfort, which approach the limit of human vision. Hence, laser display is regarded as one of the significant directions for transforming and upgrading the display industry. In this study, the technical and industrial characteristics of laser display technology are analyzed in detail based on the requirements of the industry for an independent, controllable, and safe development. The current development situation, development trend, and key problems in the laser display industry are summarized. The development roadmap of China's laser display industry is proposed. China should attempt to achieve breakthroughs in key technologies to further develop its laser display industry in an independent and controllable manner. Moreover, it should support the high-end market of the next-generation display industry and build industrial clusters for laser display.
Keywords: laser display; dual high definition; color gamut; visual comfort

1 Introduction

Information technology (IT) is a collective term for various key information chain technologies that involve the collection, storage, processing, transmission, and display of information. It is a strategic emerging industry in China. As an important component of IT and the terminal human–machine interface of the information chain, displays are widely applied in fields such as industry, transportation, communications, education, aeronautics and astronautics, satellite remote sensing, entertainment, and health care. These applications have penetrated all aspects of daily life; therefore, displays are an important aspect in the information industry. With the development and integration of future information technologies such as the fifth-generation mobile communication technology (5G), big data, and artificial intelligence, displays are becoming ubiquitous, integrated, intelligent, and more environmentally friendly; additionally, the demand for displays will increase significantly.

Laser display is a novel technique and product that uses lasers of three primary (or multiprimary) colors, i.e., red (R), green (G), and blue (B), as the light source. Color display can be realized by controlling the intensity ratio, total intensity, and spatial intensity distribution of the trichromatic lasers [1] (Fig. 1). The lasers possess high directionality, efficient monochromaticity, and high brightness. These three crucial laser characteristics allow displays to achieve a large color gamut that "approaches the human eye limit" and reproduces double high-fidelity (geometry, color) video images. Therefore, laser displays are regarded by the international industry as a "revolution in the history of human

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vision" and also deemed as a new technology following black-and-white, color, and digital displays (Fig. 2). Laser displays have already been listed as a focus for development in the *Made in China 2025 Key Area Technology Roadmap (2015)* and provide an important strategic direction for transforming and upgrading the display industry [2].

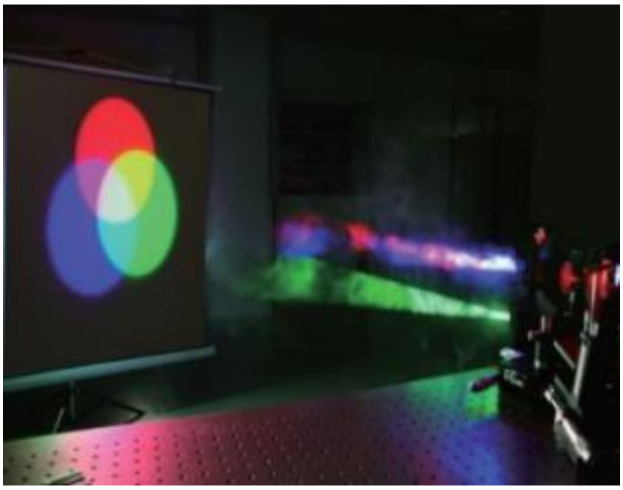

Fig. 1. Experiment of white light source synthesized using RGB laser.

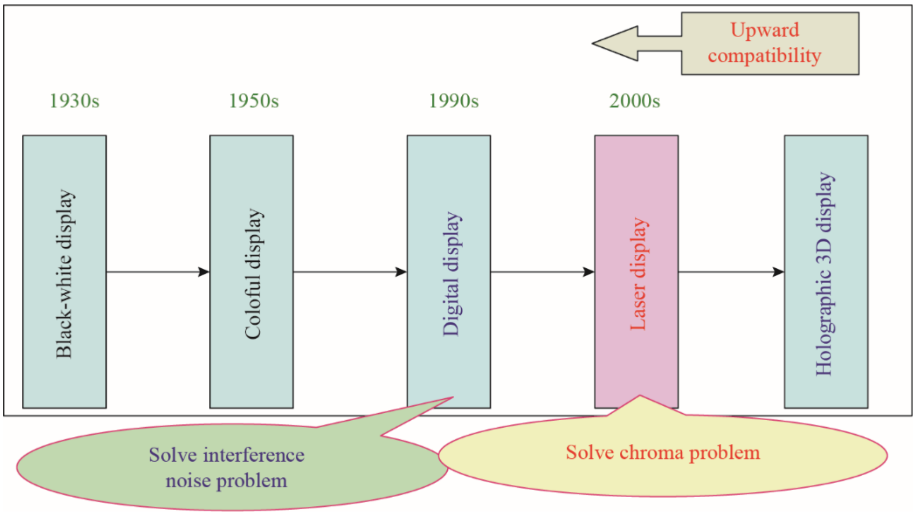

Fig. 2. Roadmap of display technology.

2 Characteristics of laser display technology

Researchers have demonstrated that 70%–80% of information acquired by humans is from vision. As the terminal for human–machine interface, displays must satisfy the viewing requirements of the human eye. Laser display is a new generation technology that can realize high-fidelity image reproduction. It retains all the advantages of digital display technology while affording several intrinsic strengths, as follows.

2.1 Double high-resolution of geometry and color

A high definition (HD) geometry indicates a high linear resolution. Studies of the human eye biology and principles of visual optics have shown that the upper limit of the human eye resolution is approximately 1′, the clear field of view encompasses 35° horizontally and 20° vertically, and the peripheral field-of-view encompasses 120° horizontally and 60° vertically [1]. Hence, the human eyes can resolve images with ultrahigh resolution and distinguish between rich and subtle colors. With its high directionality and small divergence angle, laser can deliver a (full screen) display resolution of 4 K, 8 K, or higher with ease.

An HD color involves a significant number of colors. The most significant feature of a laser display is the narrow laser spectrum known as the line spectrum (which has a spectral width smaller than 5 nm). By contrast, most other

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display sources have a band spectrum with a spectral width of 30–40 nm (Fig. 3). Because the spectral width is extremely large, a tricolor spectrum may overlap with fine colors during color mixing. Hence, the spectrum will be difficult to discriminate by the human eye, rendering it impossible to be displayed well at the terminal. When a tricolor laser with a spectral width smaller than 5 nm is used as the light source, the color purity is high and the non-overlapping of the 12-bit color number coding can be completely realized. Hence, a significant number of display colors (500 times more than the traditional display) can be realized to reflect nature's true colors more accurately [3–6].

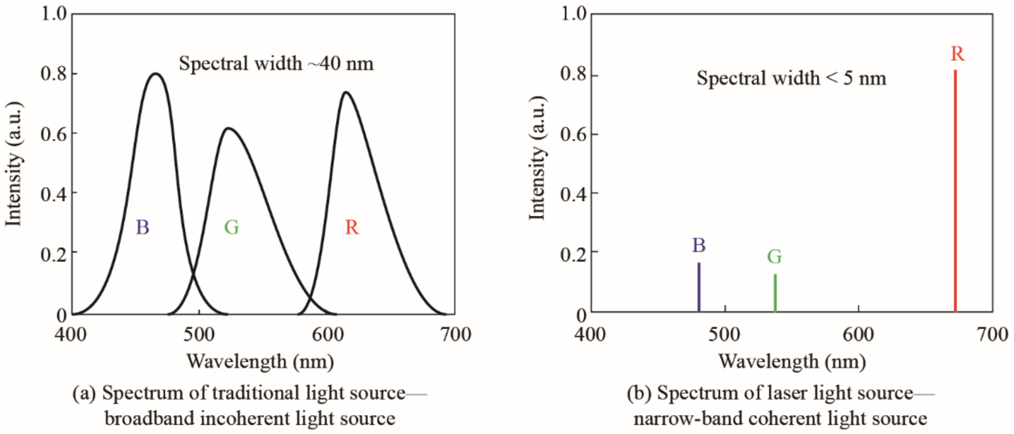

Fig. 3. Optical spectrum width of fluorescence (left) and laser (right).

2.2 Large color gamut

The light sources of the three primary colors (R, G, B) in existing color display devices tend to have a band spectrum. In the chromaticity diagram, their color gamut encompasses only a small portion identifiable by the human eyes; hence, they cannot reproduce colors with high saturation. Laser has a high monochromaticity and a line spectrum, which can form a super-large color gamut in the chromaticity diagram, as shown in Fig. 4. Hence, a more colorful display can be obtained, with a color performance two to three times better than those of traditional monitors, demonstrating unparalleled color reproduction.

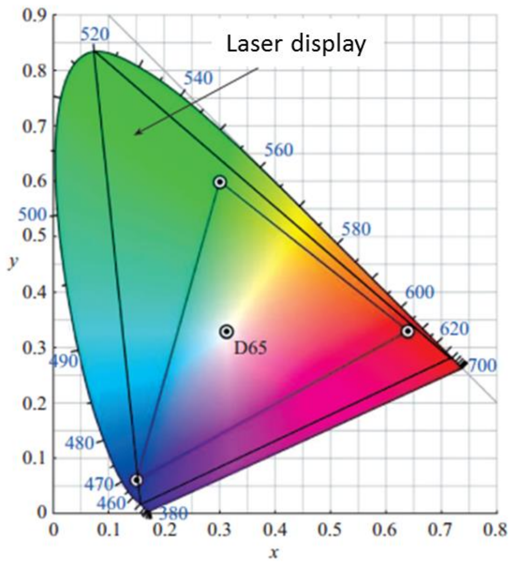

Fig. 4. Color domain coverage ratio of different display technologies in CIE 1931 chromaticity diagram.

2.3 Comfort in viewing

A laser display is rendered through reflected laser imaging, wherein reflections from objects in nature enter the human eye for imaging. The light reflected by the screen arrives at the human eye and is soft rather than dazzling. Additionally, the laser display can be viewed comfortably because its pixels are the same as those of the light-emitting area (determined by its operating principle) as well as the smooth transition between pixels (no fringe effect).

According to the visual comfort test of the Laboratory of China Electronics Standardization Institute and Beijing Union Medical College Hospital, laser displays deliver efficient viewing comfort [7].

In summary, laser displays exhibit many technological advances. Their light source has a narrow spectral width (approximately 5 nm) and can realize non-overlapping grayscale coding for 12-bit colors. Additionally, their wavelengths can be adjusted. According to the color television broadcasting standard from the National Television System Committee in the US in 1952, lasers can form a super-large color gamut that is 150% or higher than the standard. Additionally, lasers have high brightness and can be controlled accurately to within the optimum visual perception area of the human eye (8K HD geometry). The color temperature of lasers can be adjusted precisely, allowing for the easy realization of a seamlessly tiled super-large-screen display at a level of hundreds of square meters. When combined with the holographic technique, complete information regarding the wavelength (color), amplitude (intensity), and phase (stereo) of the object light can be reproduced, resulting in a true three-dimensional (3D) display. Laser display is currently the only technique that satisfies the international BT.2020 ultrahigh-definition display standard [8], fulfilling humankind's ultimate demand for fine visual effects.

Furthermore, laser displays are lightweight, low cost, and manufactured in an environmentally friendly manner. Specifically, compared with a liquid crystal television of the same size, laser displays require only half the power consumption and have a longer lifetime than 2×10^4 h; hence, they are energy-conserving and environmentally friendly. Additionally, they are compact, light, and affordable. For example, a 100-inch laser television weighs approximately 20 kg, whereas a liquid crystal television of the same size weighs approximately 150 kg. Therefore, laser televisions can be conveniently used in elevators or as home appliances. Additionally, laser displays adopt reflective imaging and hence provide viewing comfort. Laser displays are part of the green manufacturing industry and do not require large-scale investments. Compared with the significant funding of high-generation panels in the traditional panel display, where accumulative investments in the field of display panels have exceeded 1.2 trillion yuan. Laser displays have the advantages of production process with simple and low cost manufacturing. Overall, they are consistent with the developing trend of flexibility, portability, low cost, wide color gamut, and high luminous efficiency in the field of novel displays.

Therefore, laser displays can balance the markets of viewing/entertainment and information and exhibit high potential for becoming a mainstream technology in next-generation televisions, cinema projectors, and ultralarge screen display products. As a typical novel display technology, laser displays are consistent with the major national strategies of China, including the *Made in China 2025 Key Area Technology Roadmap (2015)* and the *Ultra HD Video Industry Development Action Plan (2019–2022)*. The laser display industry has become an advantageous industry that affects national interests, the population's livelihood, and future developments. Furthermore, it is an important strategic industry for safeguarding national industry safety as well as for promoting and upgrading industry transformation, representing the level of IT intelligence for the country.

3 Status of laser display technology in China and abroad

3.1 Development of laser display abroad

Laser display leaders abroad such as Japan, South Korea, and the United States has begun investigating core technologies for laser displays since the 1990s. National projects such as the US Department of Energy Plan and the Science and Technology Basic Plan of Japan were successively implemented to support research and development (R&D) in relevant enterprises. For instance, Japanese companies including Nichia Corporation and Mitsubishi Group have invested approximately 3.2 billion US dollars in the R&D of tricolor laser diodes (LDs). They managed to achieve world-leading technical and economic indicators. Specifically, the output power of a single indium phosphide (InP) red LD can attain 750 mW, whereas blue and green LDs made from gallium nitride (GaN) can achieve a single-emitter output power exceeding 4 and 1 W, respectively, with a lifetime exceeding 2×10^4 h. Texas Instruments in the US and the Sony Corporation in Japan are dominating the market for ultra HD image processing chips in laser displays, with the use of reflective digital micromirror devices (DMDs) and reflective liquid crystals on silicon, affording a resolution of 2K/4K. Regarding the technological fields of ultra HD lens and extra-large Fresnel optical films, Japanese companies such as Ricoh Co., Ltd. and Dai Nippon Printing Co. are world leaders.

In terms of the entire machine technologies, such as image processing, integration, and products development, the Japanese government have established enterprises and research institutes to perform a joint R&D into laser display techniques. Specifically, as supported by Sony Corporation, Panasonic Corporation, Mitsubishi Group, Seiko Epson, and others, the "xvYCC" large color gamut display standard has been formulated. Furthermore, these

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companies have implemented industrial chain integration worldwide, thereby maintaining their competitive advantage in next-generation display technologies in Japan. Mitsubishi Electric has successfully developed laser rear-projection, 65-inch laser, and 3D laser televisions. Seiko Epson has launched a laser front projection prototype based on 3LCD. In Europe and America, several companies have developed complete laser display machines specific to various application scenarios. For example, the German company, Jenoptik has developed laser display products for special markets such as planetariums. Evans and Sutherland, from the US, has developed a pilot simulation demonstration system that has a large screen laser display system for training fighter pilots. Barco launched a 60 000 lm laser projector with a resolution of 4 K. In 2019, this company showcased a laser cinema projector with a 4K resolution and 98.5% REC2020 color gamut based on an RGB laser source as well as a tilt and roll pixel DMD. In 2014, Christie demonstrated a 3D laser projection system with a resolution of 4K and six primary colors. In 2019, they demonstrated an RGB cinema projector with 4K resolution and 120 Hz frame rate at the Beijing International Radio, TV, and Film Exhibition.

3.2 Development of laser display in China

The development of laser displays in China is aligned with overseas progress. While the country was previously following suit, it has now reached the stage of co-developing in general and is leading in terms of industry scale. Researchers from the Chinese Academy of Sciences were the first in China to conduct R&D into laser display technology and have always been the leading domestic group in this field. In the 1970s, organizations such as the Institute of Physics at the Chinese Academy of Sciences developed a scanning laser display prototype based on a gas laser source. Supported by the National High Technology Research and Development Program of China (863 Program) and the Innovation Engineering Plan of the Chinese Academy of Sciences, Xu Yanzu from the Chinese Academy of Sciences developed the first principle prototype of laser projection display in China in 2003. By 2005, 65-, 84-, 140-, and 200-inch laser TV prototypes had been created (Fig. 5). These prototypes passed joint assessments from the Ministry of Industry and Information Technology as well as the Chinese Academy of Sciences in January 2006 and were evaluated as being at an internationally advanced level in general. These prototypes featured world-leading core characteristics, such as a wide color gamut coverage and intellectual property; additionally, they garnered several patents for the invention of core technologies. The research phase of laser displays was completed at the same time as international accomplishments, catapulting the progress of laser display from prototype to practicality. In 2006, Xu Yanzu proposed a roadmap for industrial development, using LDs with three primary colors (red, green, blue) as the core. In 2015, Xu et al. successfully developed the first 100-inch tricolor LD laser TV prototype, demonstrating the feasibility of industrialization for laser display technology. Subsequently, the team established a production demonstration line of tricolor laser displays, thereby leading the innovation chain from laser display materials, devices, and whole machines to industrial demonstration.

Fig. 5. First principle prototype of laser projection display in China.

Recently, the technology and industry of laser displays in China have progressed rapidly. These include projects from the 863 Program; the National Key Technology R&D Program of the 10th, 11th, and 12th Five-Year Plan; and the National Key Research and Development Project of the 13th Five-Year Plan. Furthermore, key materials, devices, and application technologies for laser displays have demonstrated gradual breakthroughs. In particular, tricolor LDs, which is the core of the laser display industry, as well as whole machine design and manufacturing have progressed significantly. Currently, the output power from a single red LD can reach 2 W (lifetime exceeding 1×10^4 h) in China. The maximum power from a blue counterpart is 2.8 W (lifetime exceeding 5000 h), whereas the maximum output power from a green LD can reach 500 mW. In terms of the development of the overall system in China, multiple core technologies have been patented, such as the high-power laser module, speckle suppression, and integrated manufacturing, reaching a world-leading level. A series of policies and supporting projects in this area have been introduced by the government, thereby promoting investments in laser display from key enterprises and the rapid development of this industry. Dozens of traditional home appliance firms and Internet enterprises have conducted industry layout planning into the complete links of laser displays. These companies include Hisense Visual Technology Co., Ltd., Sichuan Changhong Electric Co., Ltd., Hangzhou CASIRIS Technology Co., Ltd, Appotronics Corporation Ltd., and TCL Technology Group Corporation. The production value of laser display in China exceeded 12.5 billion yuan in 2019. With a compound annual growth rate of approximately 100% in recent years, the industry scale was at an internationally advanced level.

4 Trend analysis and challenges of laser display

To realize industrial applications using laser display technologies, prompt solutions have been demanded from four key technologies, i.e., RGB tricolor light sources, ultra HD video image technologies, key supporting materials and units, and overall design and integration (Fig. 6). Additionally, the ecosystem of the laser display industry along with independent intellectual property are expected to be created by systematically organizing the patent pool and the international standards of laser displays. Once the ecosystem is established, China's leapfrog development from a country with a large display industry to one with a strong display industry can be realized by transforming and upgrading the display industry.

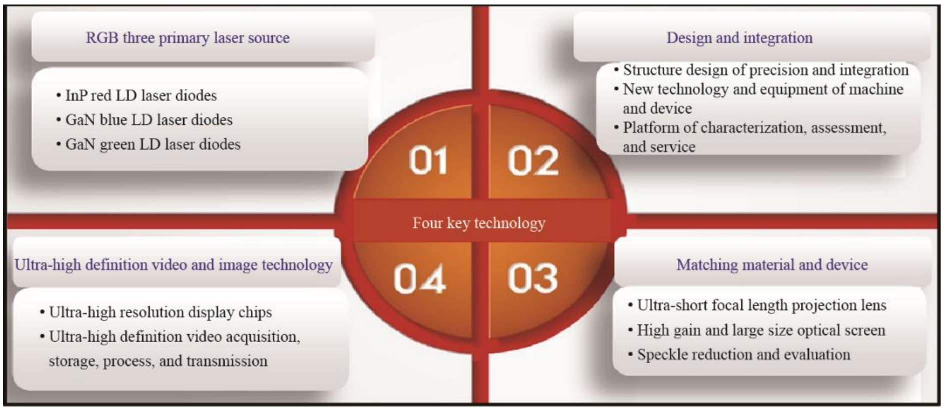

Fig. 6. Key technologies of laser display industrialization.

4.1 Tricolor laser source

Throughout the development of laser displays in recent decades, the core driving force of the industry has been the laser source, which is also the core competency for HD image reproduction in laser displays. Laser display light sources in the form of gas lasers (large volume, high power consumption, short life, difficulties in practical use), all-solid-state lasers (complex structure, low efficiency, difficulties in speckle suppression), and tri-color LD source lasers have been used (Fig. 7).

Compared with other coherent or incoherent sources, tricolor LD sources offer numerous advantages, including direct electro-excitation, high efficiency, high polarization degree, long life, high reliability, compactness, and easy adjustment of composite frequency-/space-/time-domain parameters. More importantly, their cost can be reduced by mass production via semiconductor manufacturing processes. This strength supports the cost-effective applications of laser displays in the homes of ordinary people, justifying LDs as the optimum light source for the industrialization of laser displays. The materials and devices of tricolor LDs in China have progressed significantly. For example, the power from a single red LD can reach 2 W (lifetime exceeding 1×10^4 h) in China, whereas the maximum output power from a single blue LD is 2.8 W (lifetime exceeding 5000 h), and the maximum output power from a green LD can reach 500 mW.

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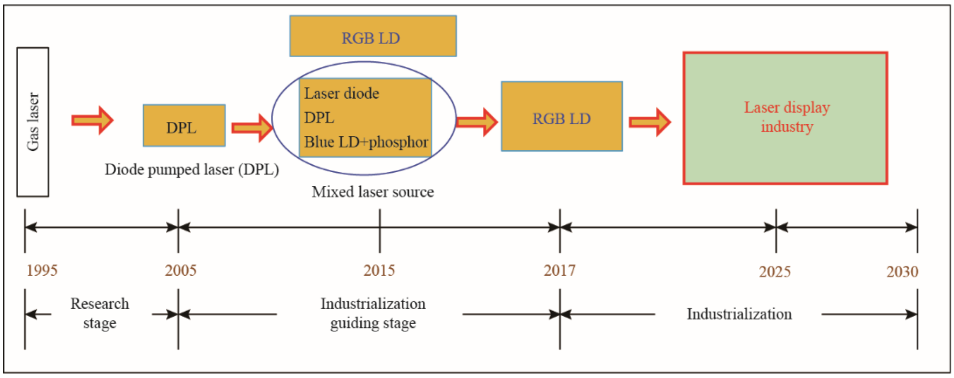

Fig. 7. Development trend of laser display technology and industrialization.

4.2 Ultra HD video image technology

Ultrahigh-resolution displays are now available, with significant global competition in 8K ultra HD TV technologies. Several sectors in China, including the Ministry of Industry and Information Technology, have issued the *Ultra HD Video Industry Development Action Plan (2019–2022)*, suggesting China's determination in constructing an ultra HD video ecosystem by 2022. Several urgent issues must be addressed for laser displays, a representative ultra HD display technology. They include the core techniques of 4K/8K ultrahigh resolution display chips, acquisition/storage/processing/transmission of ultra HD video images, biological features of the human eye, and psychological characteristics of vision. In terms of ultra HD video standards, China is progressing rapidly with independently studied and established technical standards of digital video coding and decoding. Meanwhile, the popularization of new generation information technologies, such as 5G, big data, and cloud computing has enabled the demands of high speed and broad bandwidth in video image information for laser displays, supporting ultra HD TV signals in homes.

4.3 Supporting materials and units for laser displays

Key supporting materials and units in laser displays, including optical imaging lenses with ultrahigh resolution, high gain optical screens, novel homogenization, and beam shaping materials as well as intelligent drive/display chips, are indispensable to the ecosystem. Currently, China has mastered the design and manufacturing of super short-focus lenses, preliminarily realizing mass production of 4K optical engines, including the lens and optical-mechanical structure. In terms of high-performance Fresnel optical screens, China possesses multiple patents for core design/manufacturing and has produced extra-large optical screens. Additionally, many domestically patented speckle-suppression technologies with evaluation methods have been proposed, accelerating their practical applications [9–12]. Finally, some key material growth and processing devices, such as large-scale computer numerical control processing equipment for Fresnel molds, depend significantly on import, resulting in a demand for urgent solutions.

4.4 Overall design and integration of laser display

In terms of the entire machine of a laser display, technical studies of industrial applications must be emphasized, including ultra HD, large color gamut for whole machine design, key device integration, mass production processes with high yield, reliability tests, and corresponding standards. These specifically encompass the optical design, image processing, testing, analysis, and optimization strategy to guarantee the robustness and lifetime of the entire system [13], as well as research regarding mass production processes and equipment. Motivated by the requirements of whole machine applications, key materials and devices in laser displays can be driven rapidly toward application, thereby completing the whole-chain innovation system of design, material growth, device fabrication, entire machine integration, and industrial application.

5 Main problems of laser displays in China

5.1 High external dependence of key materials and devices, causing hidden dangers to independent industrial development

The laser display industry in China has reached a world-leading level. However, core materials and devices such as RGB tricolor laser and ultra HD imaging chips have not yet achieved independence and controllability, posing major risks to industrial development.

5.2 Low degree of connection between research and industrial application; solid evaluation system not formed to guide core technology development

The R&D of key materials and devices in laser displays is not currently well-coordinated with the whole machine application, whereas the technical evaluation system for comprehensive performance testing and application surrounding key materials and units has yet to be perfected. Specifically, the gap between China and other countries is broad in terms of technical and economic indexes, such as stability, lifetime, and equipment, resulting in an incomplete linking between the upper and lower reaches in the innovation chain.

5.3 Limited industrial concentration, incomplete industrial ecosystem

Currently, many research institutions and enterprises are involved in the technical R&D and industrial breakthroughs of laser displays. However, unified deployment is lacking, with relatively weak R&D forces and scattered funding. Many firms pursue short-term, non-challenging, quick projects without any long-term planning, thereby decentralizing the current industry. Hence, an ideal collaborative innovation system of technology, talent, and intellectual property focusing on theory, key techniques, and innovative applications is lacking.

6 Suggestions for development of laser display industry in China

6.1 Strengthening top-level design to build new mechanism of state-led and resource-integrated industry development

For new-generation IT with independent innovation in China, laser displays are promoted on a strong economic, industrial scale and possess high technical integration. Therefore, it is necessary to strengthen the analysis of laser display technologies and future developments in the industry. Furthermore, planning and top-level designs for industrial development as well as the construction of new, state-guided R&D mechanisms with steadily increasing investments are necessary. Additionally, while maintaining the consistency of supporting policies in the industry, governments at all levels should strengthen their policy support for home enterprises with independent innovation abilities and core technologies. They should function jointly with independent innovation from enterprises to create security in the materials, technologies, devices, and industry, with multiple inputs from society.

6.2 Intensifying R&D in core technologies, utilizing disruptive technologies, and enhancing capability of independent innovation

It is well known that the advantages of laser displays include ultra HD, wide color gamut, high brightness, and high comfort during viewing. In China, product applications in the fields of laser TV and laser cinema have been realized, gradually forming categories of high-end display products on a world-leading industry scale. However, core technologies such as optical source and display chips are monopolized by foreign countries, thereby creating bottlenecks for the development of the industry. To retain the technical and industrial advantages of this field, joint innovation should be implemented from governments, enterprises, universities, and research institutes, with emphasis on driving by applications. Additionally, national studies into tricolor LD sources and ultra HD display chips should be strengthened to quickly improve these weak links. Additionally, prospective laser display techniques such as true 3D holographic displays should be developed to create first-mover advantages in the future.

6.3 Constructing patent pools and formulating standards and regulations to support core competency of technologies and laser display products in China

Intellectual property can be used to independently and controllably develop the laser display industry in China; furthermore, it is the most effective approach for avoiding trade barriers and promoting products worldwide. China has established a solid foundation in terms of intellectual property for laser displays, patenting more than 7 000 items, leading and participating in the formation of multiple international standards, and preliminarily establishing the intellectual property system. In the future, the core materials and devices of laser displays should be utilized to establish the entire chain of laser displays and break through constraints of core technologies. Additionally, a complete patent pool, as well as a set of technical standards and regulations, should be established such that laser displays can be used to accelerate the globalization of China’s laser display technologies and products.

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6.4 Building innovation platform of laser display, cultivating industrial ecology, constructing an industrial system for sustainable development

Focusing on the full industry chain of laser displays, a laser display innovation platform should be developed using core materials with the basis and laser display manufacturing technologies as the core such that materials/equipment will be associated with the whole machine/terminal. The platform aims to strengthen the R&D of video content products and high-speed information processing technologies that manifest the technological advantages of laser displays, address typical key techniques for industrialization, implement futuristic techniques, as well as cultivate innovation teams and talents. Comprehensively, these efforts will ultimately form the full ecosystem of the laser display industry, which includes both upstream and downstream laser display parts with independent intellectual property rights. Hence, industrial clusters can be supported and the leapfrog development of the display industry in China can proceed.

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