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Progress of optically pumped GaSb based semiconductor disk laser

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This paper reviewed the development of optically pumped GaSb based semiconductor disk lasers (SDLs) emission at 2 μm wavelength region from the aspects of wavelength extending, power scaling, line-width narrowing and short-pulse generation. Most recently, the wavelength of GaSb based SDLs has been extended to 2.8 μm. The highest output power of the GaSb based SDLs has been reached to 17 W at the temperature of 20 ˚C. By using active stabilization, the GaSb based SDL with line-width of 20 kHz and output power of 1 W was realized. Moreover, the shortest pulse obtained from the GaSb based SDLs was generated as short as 384 fs by incorporating semiconductor saturable absorber mirrors (SESAM) in the cavity.

Keywords: semiconductor disk laser; GaSb based; 2 μm wavelength

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Introduction

Laser emission in 2 μm wavelength region is particular interest for gas spectroscopy and environmental monitoring due to the weak absorption to water vapor and strong absorption to some pollutant gases, such as CH_4 and HF[1]. At present, the laser emission in 2 μm wavelength region can be obtained by GaSb based semiconductor laser, fiber and solid-state lasers doped with Tm^{3+} and Ho^{3+} [2,3]. Compared to the fiber and solid-state lasers, the GaSb based semiconductor lasers possess a number of outstanding properties due to the band gap-engineering of semiconductor gain structures. For example, the emission wavelength of GaSb based semiconductor laser can be designed from different quantum well structures and the pumping band-width of GaSb based semiconductor laser is usually wider than that of fiber and solid-state lasers.

At present, the electrically pumped GaSb based semiconductor laser has already exhibited a relatively excellent performance. However, the lasers used for gas spectroscopy, free-space optical communication, infrared countermeasures and other important applications need high power and good beam quality at the same time. While, the traditional electrically pumped semiconductor laser is difficult to obtain the laser with high power and circular diffraction limited beam. The edge emission laser has the limitation of beam quality, while the output power of the surface emission laser is low. Optically pumped semiconductor disk laser (OP-SDL) is also known as the vertical external cavity surface emitting laser. It combines the advantages of the wavelength flexibility of traditional semiconductor laser and high power with good beam quality of solid state laser[4]. Thus, it has attracted considerable interest because of their excellent beam quality and potential high power output. A typical SDL cavity is presented in Fig. 1. The SDL chip is bonded to a heat sink and an external mirror is vertical positioned in front of the chip, such that the resulting cavity maintains geometric optical stability. By using different semiconductor material systems, the SDLs emission in different wavelengths have been realized[5-7]. Furthermore, the GaSb based SDLs emission at the wavelength range of 2 μm with excellent beam quality and high power output have particularly important potential applications in many fields. At present, researchers have conducted a lot of work to improve their optical properties and have already reached a significant achievement. This paper reviewed

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the development about GaSb based SDLs emission at 2 μm wavelength region from the aspects of wavelength extending, power scaling, line-with narrowing and short-pulse generation.

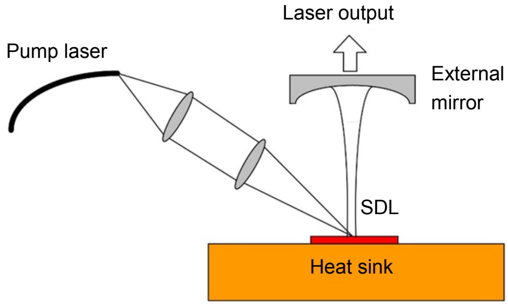

Fig. 1 | Schematic of typical SDL cavity

Development of GaSb based SDLs emission at different wavelength

Owing to the advantages of varied wavelength features, different compounds were used to expand the wavelength range in the semiconductor structure. The wavelength of the GaSb based SDLs has been extended from 2.0 μm to 2.8 μm and the gain element structures have been listed in the Table 1[8-15].

Emission at 2.0 μm

The GaSb based SDL emission at 2.0 μm was the first wavelength, of which the output power reached to watt level. As early as in 2008, Hopkins et al. reported a high power GaSb based SDL emission at 2.0 μm with good beam quality. At the temperature of 15 ℃, the output power of the GaSb based SDL can reach to 3 W and the beam quality M^2 was tested to be in the range from 1.1 to 1.4. Moreover, when the experimental temperature decreased to -15 ℃, the output power of 5 W was realized in the GaSb based SDL by using a diamond as heat sink. At this temperature, the slope efficiency of the GaSb based SDL was over 25%[8]. One year later, the output power of the GaSb based SDL emission at 2.0 μm was increased to 4 W at the temperature of 15 ℃ by Paajaste et al[9]. They designed two different gain structures and investigated the lasing characteristics of the GaSb based SDLs. They demonstrated that by using the quantum well structure of $In_{0.2}Ga_{0.8}Sb$/GaSb, an output power of 3.6 W was attained at room-temperature operation. At present, the highest output power of GaSb based SDLs was obtained at the wavelength of 2.0 μm in 2016 as shown in Fig. 2[16]. When the temperature of heat sink was set to be 20 ℃, the output power of GaSb based SDL emission at 2.0 μm can reach up to 17 W by optimizing the pump spot diameter and using a diamond as heat spreader.

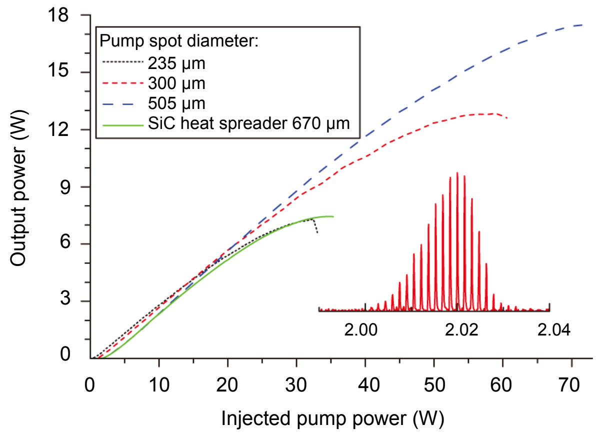

Fig. 2 | The output power curves of GaSb based SDL emission at 2.0 μm with different pump spot diameters. Figure reproduced from ref. [16], the Institution of Engineering & Technology.

Emission at 2.3 μm

In 2004, the GaSb based SDL emission at 2.3 μm with the maximum continuous-wave (CW) output power of 8.5 mW was obtained. A circular TEM_{00} low-divergence laser beam was got in the CW mode operation at the experimental temperature from 268 K to 308 K. This is the first time GaSb based SDL realized CW output[11,12]. In 2005, the CW output power of GaSb based SDL emission at 2.3 μm was significantly increased to 300 mW at room temperature operation. The semiconductor chip was bonded to a diamond heat spreader for effective thermal management[17]. In 2007, Rattunde et al. obtained the watt level GaSb based SDL operating at 2.3 μm[18]. Then, Rösener et al. reported that by using a SiC heat spreader for thermal management and a precise control of the temperature-dependent modal gain, a maximum CW output power of 3.4 W was obtained at heat sink temperature of 10 ℃[19]. In 2009, Rösener et al. realized the highest output

Table 1 Heterostructures for GaSb-based SDLs emitting at the range of 2.0~2.8 μm

Wavelength (μm)	Quantum-well/barrier composition	Reference
2.0	$Ga_{0.74}In_{0.26}Sb/Al_{0.30}Ga_{0.70}As_{0.02}Sb_{0.98}$	8
	$Ga_{0.8}In_{0.2}Sb$/GaSb	9
	$Ga_{0.76}In_{0.24}Sb_{0.90}/Al_{0.30}Ga_{0.70}As_{0.02}Sb_{0.98}$	10
2.3	$Ga_{0.65}In_{0.35}As_{0.10}Sb_{0.9}$/ $Al_{0.35}Ga_{0.65}As_{0.04}Sb_{0.96}$	11
	$Ga_{0.65}In_{0.35}As_{0.10}Sb_{0.9}$/ $Al_{0.35}Ga_{0.65}As_{0.03}Sb_{0.97}$	12
2.5	$Ga_{0.65}In_{0.35}As_{0.09}Sb_{0.9}/Al_{0.35}Ga_{0.65}As_{0.035}Sb_{0.965}$	13
2.8	$Ga_{0.55}In_{0.45}As_{0.19}Sb_{0.81}$/ $Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$	14, 15

power of GaSb based SDLs emission at 2.3 μm through a multiple gain elements configuration. When the pump power increased to 30 W, a maximum CW output power of 3.3 W was achieved at the heat sink temperature of 20 ℃[20].

Emission at 2.5 μm

In 2011, the wavelength of GaSb-based SDL was further extended to 2.5 μm. Paajaste et al. demonstrated the first GaSb-based SDL emission at 2.5 μm[13]. The gain element structure designed for emission at 2.5 μm containing 15 pairs of strained $In_{0.35}Ga_{0.65}As_{0.09}Sb_{0.91}$ quantum wells. The quantum wells were sandwiched between two $Al_{0.35}Ga_{0.65}As_{0.035}Sb_{0.965}$ barriers and grown by Molecular Beam Epitaxy on the GaSb substrate. The M^2 of the SDL was tested to be below 1.6, but the highest output power was only 0.6 W at operation temperature of 5 ℃. Up to 2016, with an efficient heat dissipation, the output power of the GaSb-based SDL emission at 2.5 μm was significantly improved, and a CW output power larger than 7 W was achieved when operated at the temperature of 20 ℃. In their work, a pumping source at the wavelength of 1470 nm was used to replace 980 nm pumping source for barrier pumping the GaSb-based SDL. The 1470 nm pumping project can realize lower quantum deficit and higher pump absorption compared to the 980 nm pumping project[21].

Emission at 2.8 μm

To explore the potential of GaSb based SDLs for longer wavelength emission, Rösener et al. prepared a GaSb based SDL emission at 2.8 μm in 2010[14,15]. Compared to the gain element structure of the SDLs emission at the wavelength from 2.0 μm to 2.5 μm, the gain element structure of the SDL emission at 2.8 μm contained the quantum well layers with more Arsenic and Indium contents. Moreover, with the increase in the emission wavelength, the thicknesses of active region and distributed Bragg reflector layer increase consequently, which makes more challenging to the epitaxial growth of the gain structure. The output power of the first GaSb based SDL emission at 2.8 μm was about 0.12 W at 20 ℃. Until 2017, the output power of the GaSb based SDL emission at 2.8 μm at 20 ℃ has been improved to be 0.85 W by the same research group[22]. The gain element structure of the GaSb based SDL was carefully modified with low quantum defect and pumped by using a 1470 nm pumping laser for high conversion efficiency. These results for 2.8 μm GaSb based SDL demonstrated the possibilities to further extend the wavelength of GaSb based SDLs toward 3 μm with good emission properties for room temperature operation.

Methods for power scaling

Up until now, many attempts have been conducted for the high output power of the GaSb based SDLs[23]. At present, the maximum CW output power of GaSb based SDLs emission at different wavelength has been listed in Fig. 3.

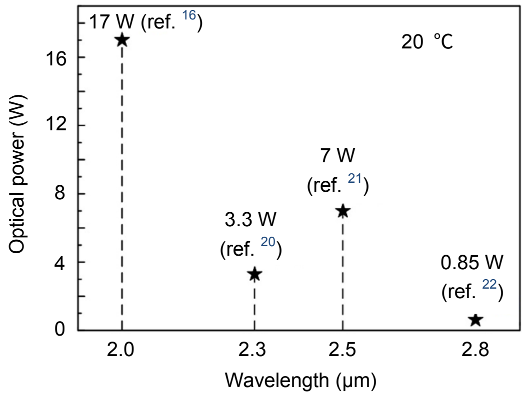

Fig. 3 | Maximum output power of GaSb based SDLs emission at different wavelength operation at 20 ℃.

To increase the output power of the GaSb based SDLs, different methods have been investigated, such as epitaxial growth optimization, lateral lasing suppression, multiple gain elements and effective thermal management.

Epitaxial growth optimization

The typical epitaxial structure of GaSb based SDLs consists of three different sections: distributed Bragg reflector (DBR), active region and confinement layer. The function of the confinement layer is to ensure carriers do not migrate to the surface of the chip. In the conventional growth procedure of GaSb based SDLs, the DBR is firstly grown on the GaSb substrate, then begin the growth of active region on the surface of DBR layer. There are some pairs of quantum well structures in the active region. Before and after the growth of active region, the growth of quantum well structures is interrupted at the interfaces. The interruption during the epitaxial growth will lead an accumulation of Indium at the interfaces, which is detrimental to the emission performance of the GaSb based SDLs[24,25]. Manz et al.[26] optimized the epitaxial growth procedure and obtained a high quality GaSb based SDL structure by using a modified sequential growth process. In this modified growth process, the DBR, active region and confinement layer of the SDL are all grown separately. During the growth process, when the preceding section has been finished, the chip is transferred from growth chamber to buffer chamber. After the new group-III gas has been stabilized in the growth chamber, the chip is taken out of the buffer chamber and then put back to the growth chamber before the next grown step of the chip is launched. Using this growth scheme, the detrimental accumulation of Indium during the growth process can be avoided and the performance of the epitaxial structure of the GaSb based SDL is considerably improved. Using this modified growth process, the output power of the GaSb based SDL has been improved by about 100%. With the SDL resonators well optimized, the maximum output power of the GaSb based SDL grown by traditional growth process is about 1.3 W, while the output power of the SDL grown by this new growth process can reach up to 2.6 W.

Lateral lasing suppression

Usually, the increase of pump spot size could realize the power scaling of the SDLs in experiment. However, the increased pump size would significantly enlarge the gain length of the chip on the horizontal plane, which obviously amplifies the educed spontaneous emission. The amplified spontaneous emission (ASE) can produce a laser on the horizontal plane of the chip, if the edges of the chip provide enough feedback. Bedford et al. indicated that the lateral lasing perpendicular to the vertical laser emission can occur as an unexpected light loss mechanism and limited the power scaling of the laser[27]. In 2011, Hessenius et al. reported that the lateral lasing could be suppressed by eliminating the Fabry-Perot cavity generated by chip edges[28]. For GaSb based SDLs, Töpper et al. first investigated the influence of lateral lasing on the high power performance in 2012. As shown in Fig. 4, in order to suppress the lateral lasing phenomenon, the side facets of the GaSb based SDL chip with sizes of 3 mm×0.6 mm were cut in a zig-zag pattern through the full thickness by using a picosecond UV-laser based micro-fabrication system. Then, this chip was bonded to a SiC heat spreader by liquid capillary method for heat dissipation. The experiment was conducted in a standard linear resonant cavity at heat sink temperature of 20 ℃ by using a 980 nm laser as pumping source. The zig-zag pattern destroyed the lateral cavity in the parallel direction of the SDLs chip formed by plano-parallel mirrors. Compared to the standard chip with cleaved side facets, no lateral lasing was observed for the modified chip. The output power of the GaSb based SDL emission at 2.0 μm was increased from 1.7 W to 2.3 W with the lateral lasing suppression[10].

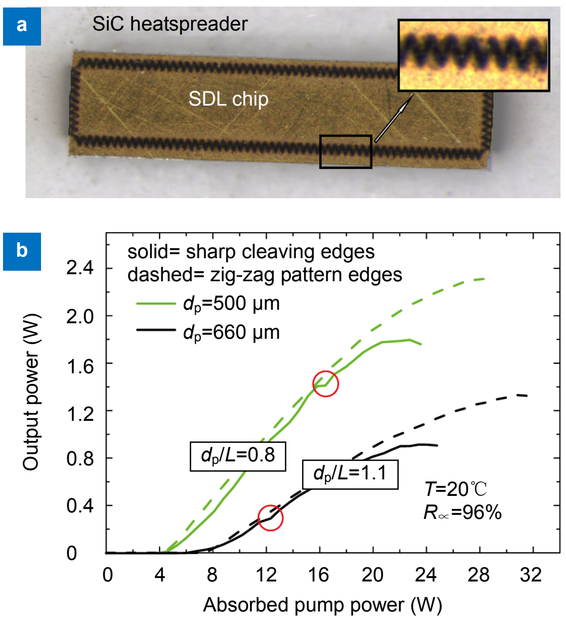

Fig. 4 | Power characteristic of the GaSb based SDL chips with patterned side facets and with cleaved side facets pumped by two different pump spot sizes. Figure reproduced from ref. [10], AIP Publishing.

Multiple gain elements

Further power scaling in SDLs with a single gain element is usually obtained by enlarging the pump spot size on the chip at an identical pumping power density. While, as discussed previously, power scaling is usually restricted by diffraction losses, lateral lasing, as well as by insufficient heat extraction. If a further output power improvement of the SDLs is demanded, a resonant cavity including multiple gain elements should be employed. This conception has already been applied in the SDLs emission around 1 μm region[29,30]. These results clearly demonstrated that the concept of SDLs with multiple gain elements can overcome the limitation of the power scaling compared with the single gain element structure. For GaSb based SDLs, Rösener et al. realized an optically pumped SDL emission at 2.3 μm by using a configuration with two separately pumped gain elements as shown in Fig. 5[20]. Compared to the SDL configuration containing one gain element, the multiple gain elements configuration allowed inputting a greatly larger number of pump light on the surface of the SDL before thermal rollover. When absorbing a 30 W pump power, the GaSb based SDL by using the two gain elements configuration emitted a maximum CW output power of 3.3 W. This record was the highest output power of GaSb based SDLs emission at 2.3 μm at heat sink temperature of 20 ℃ until now.

Effective thermal management

As the long lasing wavelength for GaSb based SDLs, the number of quantum well and DBR layers increase correspondingly, leading to a high thermal impedance and difficult thermal management for lasing and power scaling. In 2003, Cerutti et al. reported the first optically pumped GaSb based SDL. However, due to the limited effectiveness of thermal management, the first GaSb based SDL only can be operated in quasi-CW[31].

For CW operation, effective thermal management becomes imperative for GaSb based SDLs. In the year of 2004, Cerutti et al. added a semiconductor heat spreader layer on the surface of the gain chip to enhance the heat dissipation capacity of the GaSb based SDL[11,12]. Finally, a

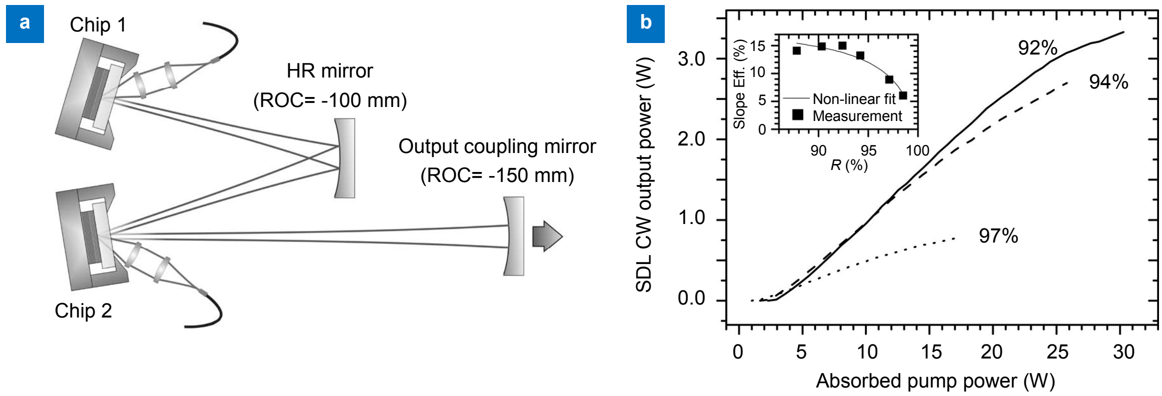

Fig. 5 | Output power of the GaSb based SDLs by using the two gain element structures at heat sink temperature of 20 °C with different reflectivity of the output coupling (OC) mirror. Figure reproduced from ref. [20], IEEE.

maximum output power of 8.5 mW operating in CW at 288 K was obtained. Moreover, to decrease the thermal load, researchers have made some efforts to reduce heat generation from pumping method. Normally, the commercial diode laser in the wavelength of 780~980 nm is used as pump source, which would cause overheating due to a large quantum defects. Schulz et al. firstly introduced a concept of in-well pumping into the GaSb based SDL. The principle of in-well pumping is that the pumping light is absorbed directly in the quantum wells. Compared to the barrier pumping, the absorbed light in the quantum wells is greatly enhanced by the high order micro resonator[32,33]. By utilizing a laser with 1.94 μm wavelength as pumping source, the quantum deficit was decreased to about 18% and a slope efficiency of 10% was achieved.

For high power operation of optically pumped GaSb based SDLs, two dominating methods have been reported that can be effective to overcome the thermal problem. Figure 6 shows the schematic diagrams of the two kind of thermal management. The first one is to get rid of the GaSb substrate and make the DBR layer soldered directly onto the surface of heat sink[34,35]. The thermal resistance between gain element and heat sink is mainly caused by the thick DBR layers and the GaSb substrate with low thermal conductivity. The substrate can be removed by chemically or mechanically methods and consequently could greatly decrease the thickness between the gain element and the heat sink. In order to get rid of the GaSb substrate, the epitaxial chips usually need to be grown in reverse order and insert an etching-stop layer between the substrate and the gain element structure.

Another option for efficient heat dissipation is using a transparent heat spreader with high thermal conductivity bonding on the surface of the GaSb based SDL by the method of liquid capillarity. This method makes the heat spreader maximized near to the gain element where majority of the heat is formed[36,37]. As early as in 2006, Schulz et al[38]. reported that when utilizing an diamond heat spreader with high thermal conductivity bonded to the top surface of the SDL chip, the CW output power of the GaSb based SDL lasing at 2.3 μm was significantly increased to >300 mW at heat sink temperature of -11.5 ℃. This thermal management method was used in the first multi-watt demonstration of a GaSb based SDL emission at 2.0 μm[39] and was also the thermal management method used in the reported GaSb based SDL with highest

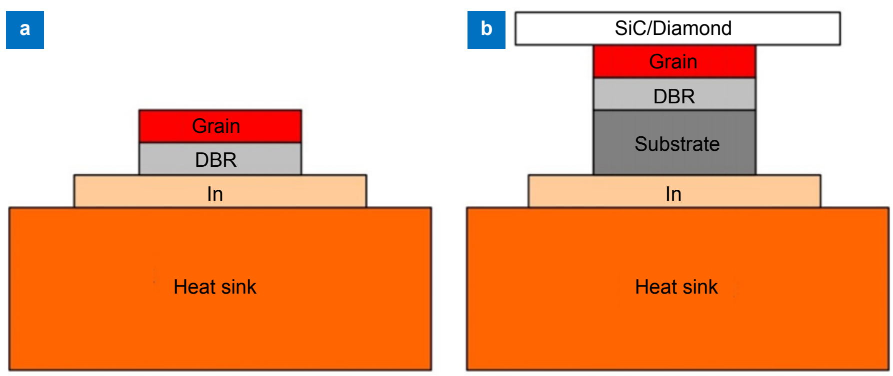

Fig. 6 | Schematic representations of the two main thermal management methods. (**a**) Substrate removing; (**b**) Intracavity heat spreader.

output power demonstrated by Holl et al[16].

Line-width narrowing

Compared to the electrical pumped semiconductor, the optically pumped SDLs with external cavity process more flexibility. The optical components for spectral and beam control can be easily integrated into the resonant cavity. For example, by inserting a birefringent filter as wavelength selective element into the resonator, a stable single-frequency laser can be generated. Considering single-frequency GaSb based SDL, a laser emission at 2.3 μm with a line-width of less than 20 kHz has been reported in 2005. While, the output power of the GaSb based SDL with narrow line-width was relatively low (5 mW)[17,40]. Before long, an output power of 680 mW in a single-frequency GaSb based SDL emission at 2.3 μm was reported by Hopkins et al. in 2007. However, the power improvement was at the cost of a significantly increase of line-width (in the MHz range)[41]. Up to the year of 2011, a combination of 200 mW output power and narrow line-width of 390 kHz performance for GaSb based SDL emission at 2.3 μm was achieved by Kaspar[42].

The line-width narrowing research of the GaSb based SDL emission at 2.0 μm was later than that of 2.3 μm. In 2011, Rösener et al.[43] demonstrated that a GaSb based SDL emission at 2.0 μm with a line-width of 9 kHz was achieved by utilizing a frequency stabilization configuration. The laser emission was in a single longitudinal mode and the output power was about 100 mW. In 2012, Kaspar et al.[44] reported that a single-mode GaSb-based SDL emission at 2.0 μm with an output power of 960 mW and a line-width of 60 kHz was fabricated. Furthermore, in the next year[45], they demonstrated a further improvement in the emission properties of a single-mode SDL emission at 2.0 μm by using a modified Pound-Drever-Hall locking structure. By using this active stabilization, up to 1 W output power and 20 kHz line-width were obtained in the GaSb-based SDL emission at 2.0 μm. This significant enhancement in output power was obtained by using a modified cavity structure, which made a highly spatial overlapping between the cavity mode and pumping spot. As shown in Fig. 7[46], for preventing the wavelength stability of GaSb based SDL from environmental noise, the cavity structure was packaged by an Al box. The character of narrow line-width with high output power makes GaSb based SDLs especially attractive for remote sense and photo-communication.

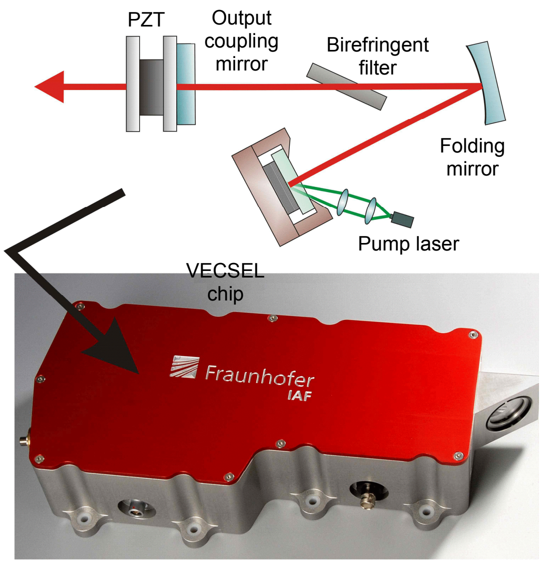

Fig. 7 | 2.0 μm GaSb based SDL with narrow line-width single-frequency emission. Figure reproduced from ref. [46], IEEE.

Short-pulse generation

Besides CW lasers, we also benefit from short pulse SDLs in this wavelength range. Because the short pulse SDLs emission at 2 μm wavelength range can be used as seed source of mid infrared super-continuum source[47] or for pumping mid infrared optical parametric oscillator. The earliest pulse generation of GaSb based SDLs was pumped by a pulse laser emission from Nd :YAG laser operating at 1.064 μm[48,49]. The pumping laser was a diode-pumped Nd:YAG laser that was continuously pumped and repetitively Q-switched by an acousto-optic Q-switch. In 2009, the 70 W peak output power at 2.0 μm was obtained when the pulse was about 300 ns[48]. While in the next year[49], a peak power of 342 W with a 143 ns pulse width was obtained, which was the highest reported peak power to date from a GaSb based SDL.

In the same year[50], Härkönen et al. reported a passively mode-locked GaSb based SDL emitting a stable picosecond pulse at 2.0 μm. A basic repetition rate of 881.2 MHz was achieved by using a semiconductor saturable absorber mirror (SESAM). The function of SESAM was to attain a self-starting mode-locked operation in the resonant cavity. The pulse energy and duration generated in the GaSb-based SDL was about 30 pJ and 1.1 ps, respectively. This was the first report on the passively mode locked picosecond GaSb based SDLs emission at 2.0 μm. In 2011, they reported a GaSb-based SDL emission at 2.0 μm, which was passively mode locked to generate a near transformation limit pulse of 384 fs as shown in Fig. 8[51]. It was the shortest pulse achieved by a GaSb based SDL emission at the wavelength range of 2 μm. As shown in Fig. 9, the resonant cavity was designed in Z-shaped structure. The mode locking element SESAM was also utilized in the resonant cavity. The InGaSb/GaSb quantum wells in the gain element and the SESAM provided the sufficient gain and absorption. Moreover, in 2012, Kaspar[52] reported a 2.0 μm electro-optically cavity-dumped SDL emitting pulses 3 ns in length with a peak power of 30 W. For generation of nanosecond pulse in the

GaSb based SDL, an intra-cavity Brewster-angled polarizer prism and a Pockels cell were used in a 35 cm resonant cavity. Through the full reflection in the birefringent polarizer, the pulse was coupled from the side of the cavity. These various 2 μm SDLs emission in nanosecond pulse are very suitable for high accuracy optical detection and ranging, as well as the material processing after further power scaling.

Future outlook

As discussed above, the GaSb based SDL has run up to a fast developing moment, making them very attractive for practical applications. Despite these achievements, there are still some developing stages that need to realize new capability and upgrade the technology to the level suitable for practical application.

While, in the future research stage, the research emphasis for GaSb based SDLs will be still focused on the aspects of wavelength extending, power scaling, line-width narrowing and ultra-short pulse generation. Wavelength extending has an inherent connection with the development of the new semiconductor structure,

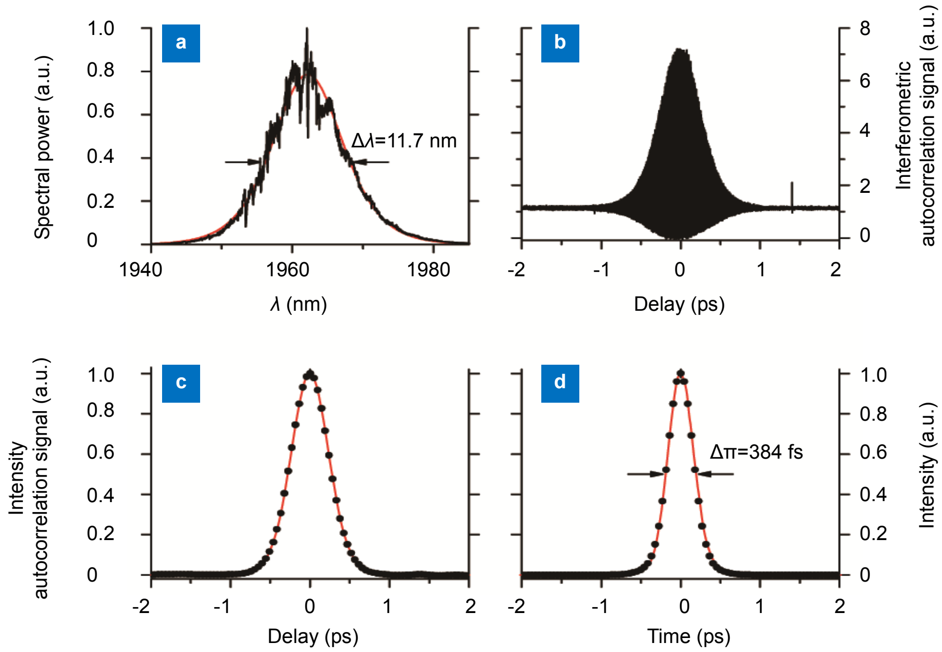

Fig. 8 | (**a**) Optical spectrum together with sech^2 fit; (**b**) Measured interferometric autocorrelation; (**c**) Intensity autocorrelation retrieved from interferometric autocorrelation data and intensity autocorrelation of bandwidth limited pulse computed from spectrum in Fig. 9(a); (**d**) Pulse shape and Fourier transform limit. Figure reproduced from ref. [51], the Institution of Engineering & Technology.

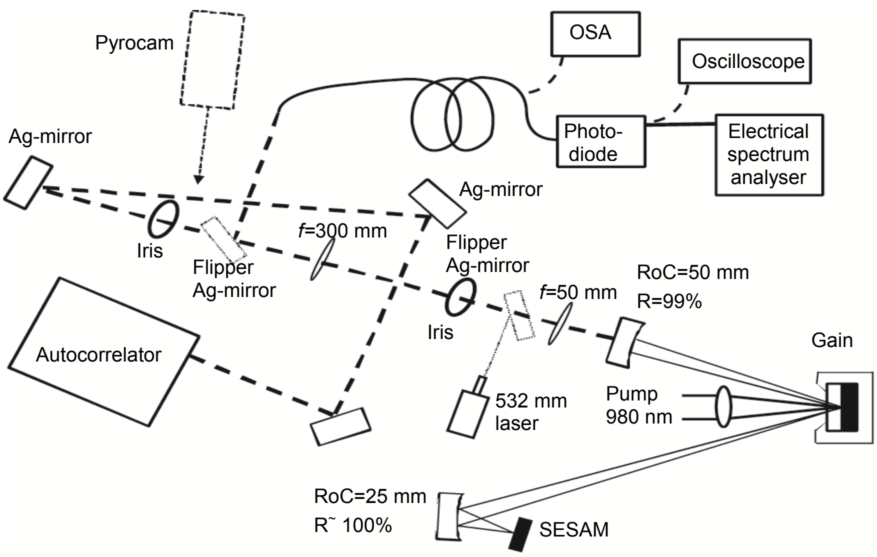

Fig. 9 | Experimental setup and optical measurement arrangement. Figure reproduced from ref. [51], the Institution of Engineering & Technology.

which can implement wavelength selection and increase the function. In any case, the emission wavelength of electrically pumped edge-emission GaSb based semiconductor laser has reached up to beyond 3 μm under CW operation[53,54]. Thus, it is hopeful for GaSb based SDLs to extend their wavelength to 3 μm region with careful deign of band-gap engineering. The wavelength extending is a key factor that has a great influence on the development of new applications. Power scaling for GaSb based SDLs is still restricted by epitaxial structure, lateral lasing and effective thermal management[55]. In the future work, the heat dissipation approaches of heat spreader and substrate removing combined with in-well pumping will become the optimal thermal management method for further improving the output power of GaSb based SDLs. In addition, lateral lasing will be the other important limitation on the further power scaling in the GaSb based SDLs. It must be considered in the design of epitaxial gain element to suppress the transverse waveguide and later feedback[26]. In recent years, the research focuses of GaSb based SDLs are turning on the aspects of line-width narrowing and ultra-short pulse generation[45,46]. At present, significant advances have already been achieved in wavelength extending, power scaling, narrow line-width and short-pulse operation. In the future, more efforts will be also conducted on these directions, which enable realization of GaSb based SDLs emission at 2~3 μm region with sufficient power and beam quality for sensing, infrared counter measures or LIDAR.

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Competing interests

The authors declare no competing financial interests.