Hetero-integrated high-peak-optical-power laser source (940 nm) for time-of-flight sensors

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1. Introduction

In recent years, there has been active development of laser diode-based sources in the 900–940 nm spectral range, specifically designed to generate high-power optical pulses with ns durations. This is primarily driven by their suitability for applications such as rangefinders and 3D LIDAR (light detection and ranging) systems based on the time-of-flight (ToF) principle that utilize Si photodetectors with an absorption peak in the mentioned spectral range[1,2]. The advantage of this approach is the widespread availability of semiconductor lasers, while the use of ns pulses ensures high spatial resolution. The development of systems that would be accessible for use in a wide range of practical applications is of utmost interest. Therefore, the relevance of developing an integrated approach to creating compact sources of high-power ns laser pulses remains high. Such sources are characterized by high efficiency, compact size, and low cost. There are two main directions associated with the development of such sources. The first direction is aimed at optimizing the design of semiconductor lasers. Studies have shown that the increase in recombination loss and internal optical loss leads to a decrease in quantum efficiency at high pulsed pump currents due to carrier accumulation in the waveguide layers of the heterostructure[3,4] and spatial hole burning[5,6]. The optimization of the semiconductor laser design, which involves optimizing the cavity length and reflectivity coefficients[5], as well as utilizing asymmetric heterostructures with low internal optical loss[7,8], aims to reduce the impact of these effects. The second direction involves the development and optimization of pulsed pumping sources for semiconductor lasers. Currently, a widely adopted approach utilizes discrete circuits with GaN field-effect transistors as high-speed current switches. This approach has shown promising results in generating high-power pulses for both single edge-emitting lasers and laser arrays[9,10] and vertical cavity surface emitting lasers (VCSELs)[11]. To achieve efficient generation of ns current pulses in such circuits, the utilization of specialized high-speed drivers for controlled turn-on and turn-off is essential in addition to individual GaN transistors.

An alternative option to develop compact and efficient pulsed laser sources is through hetero-integration, where the current switch and laser chip are combined into a single assembly. This integration enables the realization of minimal current contour length and overall dimensions, which is crucial for reducing inductance, increasing efficiency in generating high-power ns pulses, and creating multi-element laser pulse sources. However, the implementation of hetero-integrated structures using GaN transistors has thus far been demonstrated only with low-power VCSELs[12]. This limitation is attributed to the constraints...
imposed by the sizes of transistor electrodes. Significant advancements have been achieved in hetero-integrated structures utilizing high-current switches such as GaAs S-diodes \cite{13} and high-voltage silicon bipolar avalanche transistors \cite{14}. These structures have demonstrated impressive performance outcomes. Operating at voltages exceeding 100 V, they have been capable of generating current pulses with durations of approximately 1 ns with an amplitude of 40–45 A. Consequently, these structures have showcased pulses with peak powers ranging from 90 \cite{14} to 135 W \cite{13} for laser diodes based on tunnel-coupled heterostructures.

In this study, for the first time, to the best of our knowledge, an approach is proposed to create highly efficient and compact sources of high-power laser pulses, which involves the heterointegration of a semiconductor laser and a "low-voltage-thyristor"-based current switch, leveraging the high control efficiency achieved through positive feedback implemented in similar structures exhibiting electrical bistability \cite{15}.

2. Experiment and Results

To implement the current switch, it is proposed to use heterothyristor structures based on AlGaAs/GaAs with current feedback. In contrast to the previously studied hetero-thyristor structures with optical feedback \cite{16}, the proposed structure offers high manufacturability due to its simplified fabrication process, eliminating the need for multiple layers of different compositions, including quantum wells that require optimization to create photogenerated carriers in the base region. In the proposed heterostructure design, it is not possible to create an efficient laser-thyristor due to the absence of a barrier that restricts the injection of holes from the anode contact into the p-base region. The proposed structure was grown on an n-GaAs substrate and consists of the following layer sequence: a 1-μm-thick n-Al0.1Ga0.9As emitter, a composite base composed of a 0.1-μm-thick p0-GaAs layer with a doping level of 10^{19} cm^{-3} and a 4-μm-thick p-GaAs layer with a doping level of 10^{16} cm^{-3}, followed by a 1-μm-thick n-GaAs collector and a 0.5-μm-thick p-GaAs layer. For the laser diodes, an asymmetric heterostructure with a broadened waveguide was used, analogues of which previously demonstrated high temperature stability and high radiative efficiency even at high pump current levels \cite{17}. The laser heterostructure included a 2-μm-thick waveguide layer based on Al0.3Ga0.7As, with n-Al0.35Ga0.65As and p-Al0.35Ga0.65As claddings. The active region, based on an InGaAs quantum well, was shifted toward the p-cladding by 0.2 μm to discriminate high-order modes relative to the fundamental mode \cite{17}. In the present study, the heterostructures for both the thyristor switch and laser diode were grown by metal-organic chemical vapor deposition (MOCVD) in a vertical reactor on an exact [100]-oriented n-GaAs substrate at a constant temperature of 700 deg Celsius. Next, based on the fabricated heterostructures, both thyristor switch chips and laser diode chips were manufactured. The thyristor switch design incorporated specific electrode configurations. The anode electrode, with a diameter of 150 μm, was based on Ti/Pt and formed on the top p-GaAs layer. The control electrode, based on AuGe/Au, was formed on the n-GaAs collector layer. The cathode electrode was formed on the n-GaAs substrate side.

It was previously demonstrated that the use of a solid ultra-wide aperture may result in a delay in lasing turn-on between the central and outer regions of up to 450 ps \cite{18}. Therefore, it was decided to employ a laser chip design featuring a composite aperture consisting of two emitting regions, each with a width of 100 μm. These regions were separated by a 300-μm-wide unpumped passive region. The cavity length of the laser chip was 2 mm. Figure 1 depicts the schematic of the hetero-integrated assembly. The assembly consisted of an 800 μm × 2000 μm laser diode chip, which was mounted p-side down on a copper slab. Positioned on the p-side, a 500 μm × 700 μm thyristor switch chip was mounted on the laser diode. In this configuration, the thyristor switch chip comprised two segments; each had its own anode electrode and control electrode, sharing a common cathode contact. The hetero-integrated assembly was connected in parallel to an external 1.4 nF capacitor, as well as an external voltage source that charges the capacitor. Since the operation of a thyristor switch differs significantly from that of a conventional bipolar or field-effect transistor, let us consider the main phases of operation of this assembly. The initial phase involves charging the capacitor from an external voltage source. During this phase, the thyristor switch is in the off state, characterized by high resistance. This ensures efficient and rapid charging of the capacitor to the operating voltage.

During the second phase, a control current pulse is applied to the thyristor control electrode, which switches the thyristor to the on state. Turn-on delay time is a specific characteristic of thyristor switches. In general, to switch to the high-conductivity “on” state, it is necessary to accumulate a critical concentration of excess holes in the p-base region. In the proposed design, this is achieved through the control current. For the developed structures, the permissible current pulse amplitude varies in the range of 10–200 mA and determines the turn-on delay time, the minimum value of which is 10 ns, while the operating range of control pulse durations, dependent on the amplitude, is 10–100 ns.

![Fig. 1. Schematic depiction of the hetero-integrated assembly "laser-heterothyristor switch."](Image)
It is important to note that the dynamics of thyristor switch turn-on are not influenced by the control pulse profile, which significantly simplifies working with this device. In contrast to transistor structures, the transition speed to the on state with high conductivity in thyristor switches is determined by the feedback efficiency and is independent of the control signal. The third phase involves the thyristor operating in the on state. During this phase, the laser diode is pumped by a current pulse resulting from the discharge of the capacitor. The amplitude and duration of the current pulse generated within the hetero-integrated assembly circuit are determined by the speed at which the thyristor switches to the on state, as well as the operating voltage to which the external capacitor was charged and its nominal value. Once the capacitor is fully discharged, the thyristor switches back to the off state, and the circuit is ready to initiate another cycle of capacitor charging.

To investigate the dynamic characteristics of the hetero-integrated assembly comprising the laser diode and hetero-thyristor switch, experimental studies were conducted on a dedicated test bench. The test bench was equipped with an optical system designed to create an enlarged image of the laser diode’s output aperture, as well as an optical signal registration system. The registration system consisted of a high-speed photodetector with a bandwidth of 20 GHz, a scanning system capable of traversing along the formed image, and a sampling oscilloscope with a bandwidth of 50 GHz. This approach facilitated both the investigation of spatial dynamics of lasing turn-on and the accurate measurement of the integral shape of the laser pulse, which is important when dealing with high-power lasers featuring a wide aperture whose width exceeds the size of the high-speed photodetector’s receiving area.

The laser pulses generated at different operating voltages of the hetero-thyristor switch are depicted in Fig. 2. It can be seen that the laser pulses exhibit a maximum peak power of 33 W with a duration of 3 ns at an operating voltage of 55 V. The inset of Fig. 2 illustrates the correlation between the pulse duration and operating voltage.

At initial voltages of 20 V, the laser pulse duration reaches its maximum at 4.4 ns. As the operating voltage increases to 35 V, a noticeable reduction in duration to 2.9 ns occurs, and with further increases in operating voltage and peak power, the duration remains relatively stable at around 3 ns. Pulse broadening at minimum operating voltages can be attributed to a decrease in the speed of transients within the hetero-thyristor switch, which is confirmed by the study of dynamics in external capacitor discharge. Figure 3 shows the spatial dynamics of each emitting aperture of the laser chip. It can be seen that each aperture exhibits laser dynamics characterized by a distinct intense (up to

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**Fig. 2.** Laser pulses obtained for the hetero-integrated assembly “laser–heterothyristor switch” at various operating voltages of the heterothyristor switch. The inset shows the laser pulse width as a function of the operating voltage of the heterothyristor switch.

**Fig. 3.** Lasing dynamics of the hetero-integrated assembly at an operating voltage of 55 V. (a), (b) Time-resolved near field obtained through linear interpolation of 36 curves measured at 2.7 μm intervals along the x-axis. (c) Measured total output powers of laser pulses, with filled areas indicating contributions from different emitters (LD1 and LD2 shown in Fig. 1). (d) Turn-on time distributions along the apertures of different emitters.
15 V) and narrow (up to 100 ps) peak at the leading edge. This peak signifies the initial operation of the laser part in the gain-switching mode and is clearly distinguishable from the rest of the pulse at low operating voltages corresponding to low pump current amplitudes. With appropriate optimization of the laser heterostructure design, this effect can be further utilized to create compact and high-power sub-ns laser sources. Another feature of the laser dynamics is associated with the mismatch between the turn-on moments of lasing generation in the first and second emitting apertures. At a voltage of 20 V, the mismatch reaches 265 ps and decreases to 140 ps with second emitting apertures. At a voltage of 20 V, the mismatch reaches 265 ps and decreases to 140 ps. Nonetheless, this effect does not significantly affect the integral lasing dynamics in the main part of the pulse. This indicates the absence of mutual influence between the emitting apertures and the efficient suppression of optical coupling between them. Nonetheless, this effect becomes noticeable for the first gain-switching peaks, and specific optimization of the emitting aperture design may be necessary to generate sub-ns pulses. A study of the turn-on dynamics along the emitting aperture reveals that the main central region of the aperture turns on first, exhibiting a negligible mismatch of up to 10 ps, while the edge regions experience a more noticeable turn-on delay of up to 60 ps. This observation may indicate the involvement of new modal structures, although their contribution to the overall pulse is insignificant.

Other important characteristics include the far-field pattern and emission spectra of the laser. The time-averaged lateral and vertical divergences are shown in Fig. 4. In the inset of Fig. 4(a), the distribution of laser beam intensity in the far field is shown which is obtained using a CCD camera. It can be observed that in the vertical direction, there is a Gaussian-like distribution, indicating the laser’s operation in the fundamental mode. However, in the horizontal direction, the field exhibits several local peaks, characteristic of the multimode operation mode commonly seen in wide-aperture semiconductor lasers. For the studied range of pump currents, the far fields exhibit stable characteristics, with a lateral divergence of 7 deg and a vertical divergence of 12 deg, which is important for the efficient use of focusing micro-optics [Fig. 4(a)]. The lasing spectra are shown in Fig. 4(b). It can be seen that the spectrum peak corresponds to a wavelength of 940 nm and does not shift across the studied range of pump currents. However, the spectral width increases from 4 to 7 nm.

3. Conclusion

The presented findings demonstrate that the vertical heterointegrated assemblies, utilizing a low-voltage heterothyristor-based current switch, offer a compact size and high efficiency in generating high-power ns laser pulses. The study reveals that the ability to realize gain-switching mode during lasing turn-on provides a sub-ns leading edge, approaching the achieved peak power in the main part of the pulse. It is noteworthy that by achieving synchronization of the leading edges of pulses from individual emitters with an accuracy of up to 20 ps, it becomes possible to reach a peak power of 38 W, while maintaining a turn-on edge duration of less than 70 ps. This feature indicates the potential for achieving high spatial resolution in the ToF LiDAR systems.

References