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Seeding of a titanium sapphire oscillator by a vertical-cavity surface-emitting laser in the nanosecond range

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A GaAs/AlGaAs vertical-cavity surface-emitting laser was used to seed a titanium-sapphire laser oscillator. Both lasers were pumped synchronously by the same frequency-doubled Nd:YAG laser in the nanosecond range. Even at low injection level, we obtained a strong narrowing of the emission spectrum of the oscillator (from 30 to 1 nm), as well as its tunability over a broad range of wavelengths (from 775 to 805 nm).

There is currently a growing interest in all-semiconductor vertical-cavity surface-emitting lasers; indeed, these structures present several attractive properties such as low threshold, good output beam quality, reliable fabrication processes or possibility of monolithic integration.[1,2] On the other hand, a lot of work is currently devoted to the development of compact tunable solid-state lasers.[3] With its broad spectral band of fluorescence, the Ti:Al_2O_3 crystal presents many advantages in terms of reliability, ease of use, and long-term stability.[4] A classical way to achieve the tunability of an oscillator is by using intracavity selective passive elements (prism, filter, etc.). Another one is by "injection seeding."[5–8] We present here an original experiment consisting of seeding a Ti:Al_2O_3 oscillator by a GaAs/AlGaAs multiple-quantum-well (MQW) vertical-cavity surface-emitting laser (VC-SEL). Both lasers were pumped synchronously at 25 Hz by the same frequency-doubled Nd:YAG laser in the nanosecond range.

The GaAs/AlGaAs VC-SEL consists of a MQW active medium sandwiched by two integrated AlAs/$Al_{0.2}Ga_{0.8}As$ Bragg reflectors. The whole structure has been described elsewhere.[9] We need only bear in mind its most noteworthy features:

(i) it has been explicitly designed for optical pumping (no electrical connections);

(ii) when optically pumped, the microcavity exhibits a two-wavelength laser behavior with an intermode greater than 30 nm;

(iii) the light is emitted in a 7° aperture conical beam devoid of astigmatism;

(iv) the spectral width of each mode is about 1 nm due to the short cavity length;

(v) a slight inhomogeneity of the thickness and/or composition of the layers makes it continuously tunable by properly selecting the zone to be pumped.

For that purpose the sample can be translated laterally in front of the pump beam (0.9 μJ pulses focused on a 70-μm-diam spot). Let λ_i denote the wavelength of the injection signal, tunable from 775 to 805 nm.

The linearly polarized oscillator consists of a plano-concave cavity. The 20-mm-long Brewster's angle cut Ti:Al_2O_3 crystal is longitudinally pumped at 532 nm through a dichroic high-reflection concave mirror M_1 of 1 m radius of curvature. The transmission of the plane output coupler M_2 is 40%. The energy of the pump pulses is a few mJ, their temporal duration is about 10 ns. The emission spectrum of the laser is determined by the spectral gain of the crystal and by the mirror coatings. The pulse duration is about 40 ns and the output energy is 0.4 mJ for a pump energy of 2.7 mJ. The beam exhibits a TEM 00 spatial profile.

Both the oscillator and the VC-SEL are synchronously pumped by the same frequency-doubled Nd:YAG laser (532 nm, 10 ns). The experimental setup is schematically represented in Fig. 1.

A small part of the pump beam (0.9 μJ) is taken and directed toward the semiconductor microcavity. Its emission is collected through a dichroic beamsplitter and sent into the main cavity. In order to protect the semiconductor sample from the strong (and possibly destructive) energy delivered by the oscillator, an optical isolator allows the light to propagate only from the unpolarized VC-SEL toward the titanium-sapphire and not the other way round. It consists of a half-wavelength plate (λ/2), a Faraday rotator, and a two-way cubic polarizer (P). The maximum output energy of the VC-SEL is about 2 nJ but the energy actually injected inside the titanium-sapphire cavity is estimated to be no more than 12 pJ (maximum energy available at 795 nm).

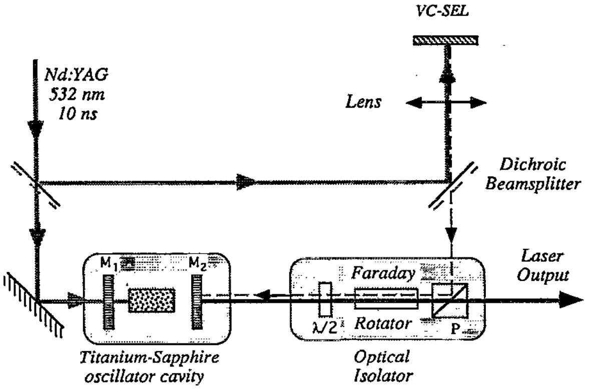

FIG. 1. Experimental setup.

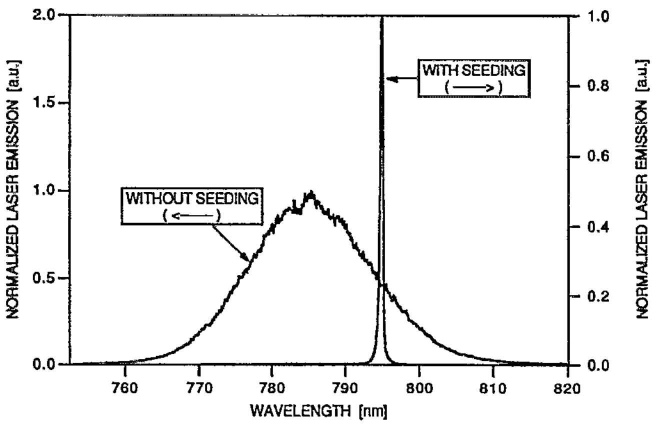

FIG. 2. Emission of the titanium-sapphire with and without seeding.

The beam is detected by a spectrometer followed by an optical multichannel analyzer (OMA) providing background-corrected 20-shot-accumulation-time-integrated spectra. The pulse-to-pulse variation is negligible due to the good stability of the Nd:YAG pump laser. Without any seeding, the free running spectrum of the oscillator is about 30 nm broad, centered around 785 nm. In the presence of the seeding, it exhibits a much narrower shape. With the VC-SEL tuned to $\lambda_i \approx 795$ nm we obtain the typical spectrum represented in Fig. 2.

The spectral bandwidth of the emission is greatly reduced. It becomes similar to that of the VC-SEL itself (≈1 nm). We can also observe that the temporal duration of the emitted pulses remains the same (about 40 ns). The emission wavelength of the oscillator in the presence of seeding is tunable by tuning the VC-SEL, as shown in Fig. 3.

The efficiency of the seeding depends on the energy actually coupled back from the VC-SEL to the oscillator. It can be characterized by a so-called "injection efficiency," noted as η and defined as the fraction of energy included in the same spectral range as that of the injection signal (of energy E_i), referred to the total amount of energy emitted (over the whole range of initially available wavelengths). We obtain both by integrating over definite spectral ranges the spectra provided by the OMA.

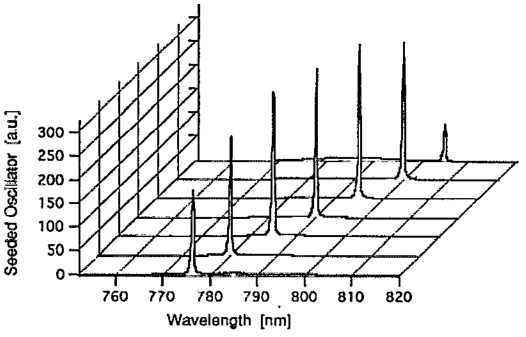

FIG. 3. Schematical representation of the tunability of the titanium-sapphire in the presence of seeding by translating the VC-SEL sample in front of the pump beam.

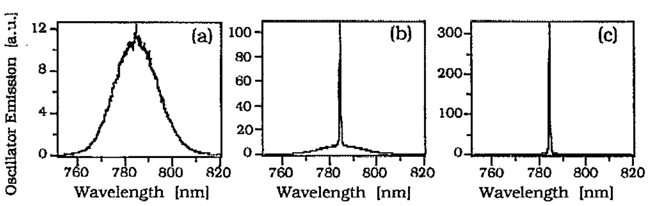

FIG. 4. Construction of the seeding process ($\lambda_i \approx 785$ nm) for different values of the injection efficiency η; (a) $E_i \leq 0.01$ pJ, $\eta = 14\%$; (b) $E_i \approx 0.5$ pJ, $\eta = 36\%$; (c) $E_i \approx 8$ pJ, $\eta = 86\%$.

We investigated this efficiency by varying the amount of injection signal at $\lambda_i \approx 785$ nm. At low level of seeding, only a small fraction of the total energy provided by the titanium-sapphire is emitted in the same spectral range as that of the injection signal. Such a case is shown in Fig. 4(a), whereas at higher injection levels the fraction of energy remaining inside the lateral "wings" of the spectrum becomes smaller and smaller [Figs. 4(b) and 4(c)].

Moreover, we have verified that at $\lambda_i \approx 795$ nm the injection efficiency of the system can reach 100%. This means that even at a relatively low level of seeding (≈12 pJ), we are able to transfer all the energy available in the Ti:Al_2O_3 crystal from a 30-nm-wide spectral range initially into a narrow band of about 1 nm; its exact width appears to be limited only by the spectral characteristics of the microcavity.

This way we have achieved a strong spectral narrowing of the oscillator emission without energy losses and without recourse to any extra selective element inside the oscillator cavity.

We have demonstrated the possibility of seeding a pulsed-titanium-sapphire oscillator by a GaAs/AlGaAs VC-SEL, both cavities being synchronously pumped by the same frequency-doubled Nd:YAG laser in the nanosecond range. We took advantage of the slight inhomogeneity of the semiconductor device to tune the oscillator continuously over a broad spectral range (775–805 nm), with a strong narrowing of the emitted spectrum (up to 1 nm). We investigated the injection efficiency of the seeding and we showed experimentally that even a relatively low injection level (as low as 12 pJ), all the energy available inside the pumped crystal can be emitted in a narrow spectral range which appears to be limited only by that of the VC-SEL itself.

The good output beam quality of the VC-SEL makes it particularly attractive for injection seeding as compared to classical laser diodes. Admittedly we are still limited by its spectral width due to its short cavity length. Nevertheless we believe that the use of optimized designs such as three-mirrors extended-cavity VC-SELs[10] could ultimately provide an injection signal selective enough to be consistent with a single-longitudinal-mode behavior of the oscillator.

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