Transient response of wavelength switching in multicavity mode-locked laser diodes

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We report the transient response of wavelength switching in multicavity laser diodes. Spatially separated Bragg gratings embedded in a single fiber are used to map optical emission wavelength to photon round-trip time in an external cavity mode-locked laser diode. Transient emission wavelength and mode-locked pulse formation are explored by switching applied radio frequency modulation. Initial conditions are found to dominate transient response. A hot photon cavity has a characteristic rise time corresponding to approximately two photon cavity round trips. A cold photon cavity exhibits significant turn-on delay and rise time that depends on applied radio frequency signal power and is independent of above threshold steady-state current bias. [S0003-6951(96)01950-X]

The temporal development of both lasing light intensity and spectral content is fundamentally influenced by the average number of round trips made by photons inside an optical resonator. To date, this important and basic effect has not been explored in any depth. In fact, only recently has the term cavity formation been introduced to describe the specialized case of an adiabatically decoupled optical emission time sequence into well defined lasing modes.[1] In this letter, we report results of experiments to determine the response of an external cavity model-locked laser diode when emission wavelength and cavity length are simultaneously switched.

Figure 1(a) shows the experimental arrangement used to measure transient response. Optical emission at $\lambda=1.3$ μm wavelength from an antireflection (AR) coated facet of a multiquantum well semiconductor laser diode is coupled with 45% efficiency into a lensed single-mode fiber containing 10 Bragg gratings. The fiber gratings[2–4] are spaced 2 mm apart with center wavelengths placed at approximately 1 nm intervals covering the spectral range from $\lambda=1307$ nm to $\lambda=1316$ nm. The steady-state light-current $(L-I)$ characteristics of the laser diode in this cavity are shown in Fig. 1(b). The threshold of the laser in the external cavity is $I_{th}=9$ mA and the inset in Fig. 1 shows the spectrum under steady-state current bias, $I_{dc}=30$ mA.

Mode-locked light output is switched to a particular wavelength by applying a radio frequency (rf) signal to the diode that corresponds to a grating defined photon cavity round-trip time, τ_{CAV}. Spectrally resolved transient response is measured using a microwave switch to gate the rf signal, a spectrometer to select detected wavelength, a high-speed detector, and a sampling oscilloscope.

Figure 2 shows measured optical pulse width, τ_{pulse}, as a function of rf detuning for an external cavity formed using linear fiber gratings centered at $\lambda=1312$ nm and $\lambda=1309$ nm spaced 1 cm apart. As expected for an actively mode-locked device,[5] τ_{pulse} decreases sharply as the applied rf approaches cavity resonances defined by the two Bragg gratings. The minima in pulse width at frequency $f=2.14$ GHz and

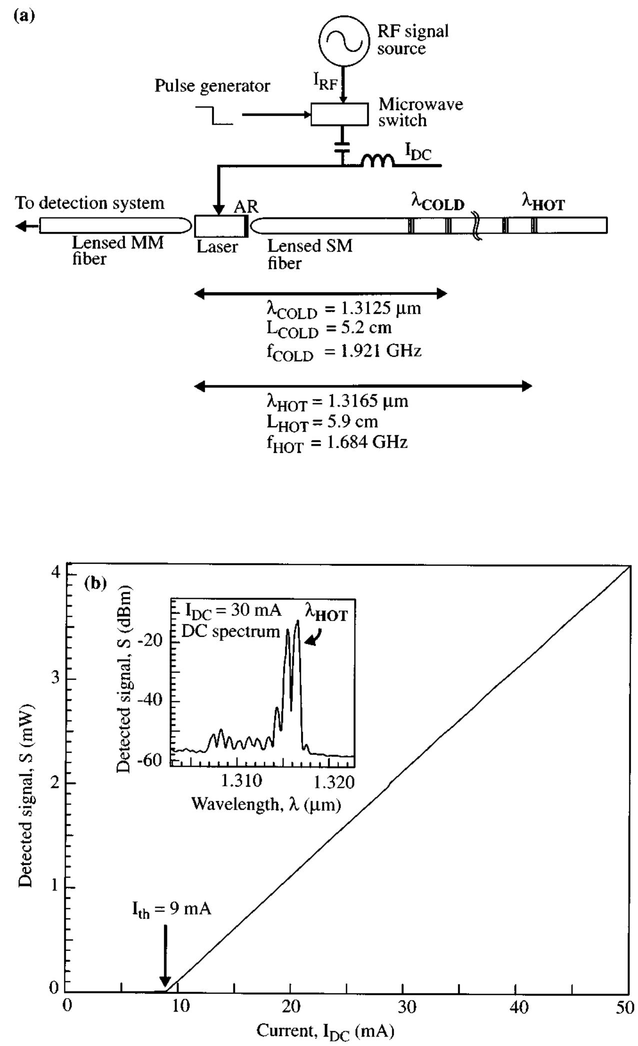

FIG. 1. (a) Experimental arrangement to study transient characteristics of an external cavity actively mode-locked laser diode. The AR coated laser obtains optical feedback from Bragg gratings embedded in the single-mode fiber that is used to define lasing wavelength λ, cavity length L, and resonance frequency f. (b) External cavity laser diode $L-I$ characteristic showing $I_{th}=9$ mA. The inset shows the optical spectrum for $I_{dc}=30$ mA with $\lambda_{HOT}=1316.5$ nm. The as-cleaved multiquantum well laser diode threshold current is $I_{th}=6$ mA.

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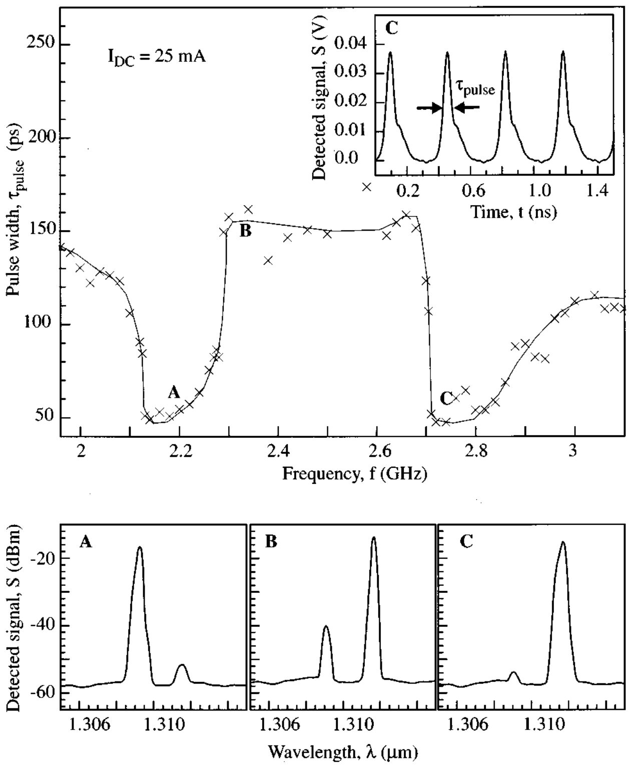

FIG. 2. Measured full width half-maximum pulse width τ_{pulse} as a function of applied rf for an actively mode-locked external fiber grating cavity laser diode. The laser is biased at $I_{\text{dc}}=25$ mA and a small fraction of the incident 24 dBm rf signal power is absorbed by the laser due to impedance mismatch. The linear Bragg gratings are 1 cm apart, centered at wavelength λ=1309 nm and λ=1312 nm, and exhibit cavity resonances at 2.14 and 2.74 GHz.

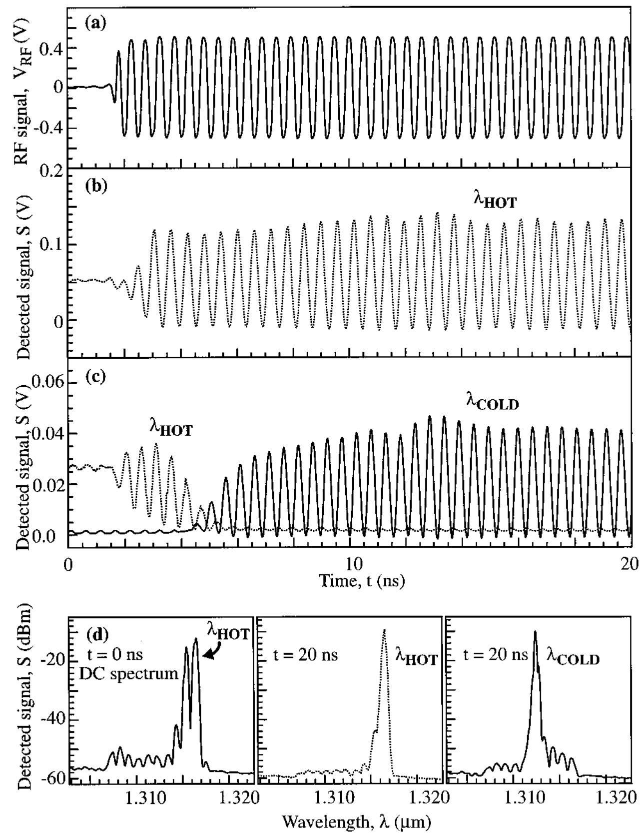

FIG. 3. (a) Transient rf wave form applied to the laser diode. 24 dBm of rf signal power incident on the laser is used to switch the optical wavelength of the light output. (b) Hot photon cavity response to achieve active mode locking using $f_{\text{HOT}}=1.684$ GHz, $\lambda_{\text{HOT}}=1316.5$ nm and $I_{\text{dc}}=30$ mA. (c) Cold photon cavity response to achieve active mode locking using $f_{\text{COLD}}=1.921$ GHz, $\lambda_{\text{COLD}}=1312.5$ nm and $I_{\text{dc}}=30$ mA. It takes five photon cavity round trips for the λ=1316.5 nm wavelength component to decay after which the spectral intensity at λ_{COLD} starts to grow with a 50% rise time of seven photon cavity round trips. (d) Optical spectrum at the indicated times.

$f=2.74$ GHz correspond to $1/\tau_{\text{CAV}}$ for each Bragg grating defined cavity. The locking range is determined by the approximate 2 mm length of the linear Bragg grating.

Figure 3 illustrates results of measuring transient response using a microwave switch to turn on the rf signal applied to the laser diode. As shown in Fig. 3(a), the applied rf signal has a 1 ns response time. In these experiments, the diode is biased at $I_{\text{dc}}=30$ mA so that prior to applying the rf signal the laser light output has spectral components at λ=1316.5 nm and λ=1315.5 nm [see Fig. 3(d)]. If the applied rf signal selects a mode-locked lasing wavelength that is already lasing, we define this to be a hot photon cavity. The results shown in Fig. 3(b) indicate that it takes approximately two photon cavity round trips after the rf signal, $f_{\text{HOT}}=1.684$ GHz, is applied for the laser to switch its mode-locked output to the wavelength $\lambda_{\text{HOT}}=1316.5$ nm. If the applied rf signal selects a mode-locked lasing wavelength that is not already lasing, we define this to be a cold photon cavity. The results in Fig. 3(c) show that by applying a rf signal, $f_{\text{COLD}}=1.921$ GHZ, the lasing wavelength can be switched to λ_{COLD} but it takes five photon cavity round trips for the λ=1316.5 nm wavelength component to decay after which the spectral intensity at λ_{COLD} starts to grow with a 50% rise time of seven photon cavity round trips.

The transient time $\tau^{50\%}$to reach 50% of the steady-state value after the switch is turned on can be normalized to τ_{CAV} by defining $n^{50\%}=\tau^{50\%}/\tau_{\text{CAV}}$. In Fig. 4 we show results of measuring $n^{50\%}$ as a function of I_{dc} for both hot and

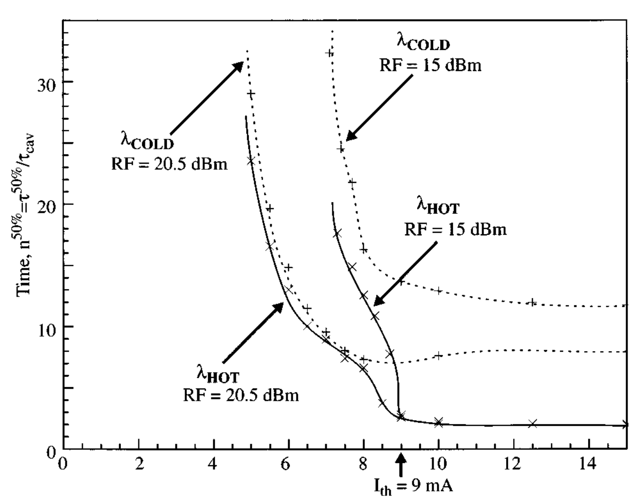

FIG. 4. Normalized transient time, $n^{50\%}=\tau^{50\%}/\tau_{\text{CAV}}$, to reach 50% of the steady-state response after the rf signal is applied. Above threshold, the transient time for λ_{HOT} is two round trips independent of I_{dc} and incident rf signal power while that for λ_{COLD} decreases with increase in rf signal power. Below threshold, the transient response of λ_{HOT} tends to that of λ_{COLD}, increasing with decrease in I_{dc} and rf signal power. Curves joining data points are to guide the eye.

cold photon cavities and for different applied rf signal powers. When $I_{dc}>I_{th}$, the value of $n^{50\%}$ for the hot photon cavity is independent of the rf signal power and I_{dc}. For $I_{dc}<I_{th}$ the transient response time increases rapidly with decreasing I_{dc}. Below threshold, $n^{50\%}$ decreases with increasing rf signal power.

The transient response time of the cold photon cavity decreases with increase in incident rf signal power. Above threshold $n^{50\%}$ for λ_{COLD} is independent of I_{dc} and depends on the incident rf signal power. Below threshold, there is an increase in the transient time for λ_{COLD} with decrease in I_{dc} at all rf signal power levels. The increase in $n^{50\%}$ with decrease in dc bias current just below threshold is more rapid for λ_{HOT} than for λ_{COLD}. As the laser is biased further below threshold the transient response time for λ_{HOT} tends towards that of λ_{COLD}. This suggests that the transient response time when switching lasing wavelength and cavity length depends on the number of ''hot photons,'' photons corresponding to the wavelength and lasing cavity switched to, present initially before the rf signal is turned on.

In this letter we have studied the transient response of an AR coated semiconductor laser in multiple external cavities to switching of the lasing wavelength and cavity length. The lasing wavelength and cavity length are switched by applying a rf signal. This novel technique to switch has an optical discrimination ratio of greater than -40 dB. The transient switching time depends on the number of hot photons present initially before the rf signal is applied to accomplish the switching. The above threshold transient response time of a hot photon cavity is two cavity round trips and is independent of the dc bias level and applied rf signal power. The above threshold transient response time of a cold photon cavity is qualitatively different, exhibiting a turn-on delay, slower rise time, and a dependence on applied rf power. Below threshold, the transient time of the hot photon cavity tends to that of the cold photon cavity, increasing with decrease in I_{dc} and rf signal power.

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