다이오드 레이저를 이용한 새로운 짧은 광펄스 생성방법

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A New Method of Optical Short Pulse Generation Using Diode Lasers

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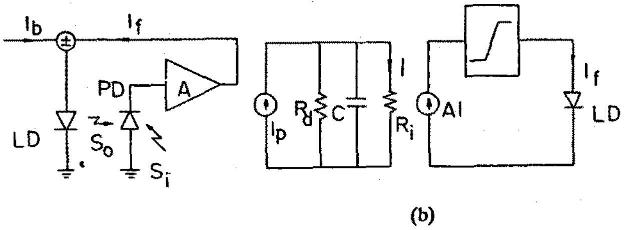
ABSTRACT

A new method optical short pulse generatioin using diode lasers under the negative electro-optic feedback are proposed. The self-pulsing is induced by feedback itself and the pulse is formed by the interaction of feeback signal and the dynamics of the diode laser. The simulated pulse width is on the order of picosecond with several *GHz* repetition rates.

Variours method of optical short pulse generation using diode lasers are reported. The shortest pulse was generated by mode locking. On the order of ten picosecond optical pulses can be generated by applying large signal modulation of sinusoidal or pulse signal to the diode laser and Q swthing. Recently optical short pulses are generated by using the electro-optic feedback to self-pulsed solitary [1,2] or external cavity diode laser[3]. The feedback reduces pulse width and increases short term stability. And mothod of delayed feedback is also studied[4]. In this paper we propose a new method of optical short pulse generation based on negative electro-optic feedback. The self-pulsing is induced by feedback itself and the pulse is formed by the interaction of feeback signal and the dynamics of the diode laser. The condition of the self-pulsing and the effects of the gain saturation and the spontaneous emission factor on the self-pulsing are also studied. The simulated pulse width is on the order of picosecond with several *GHz* repetition rate. In this method modulation signal and critical optical alignment are not required.

The proposed device consists of a diode laser, a photo-detector, and an amplifier. The schematic diagram and the equivalent citcuit are shown in Fig. 1. To model the feedback network, we simplify it as a one pole low-pass filter which has amplification, cut-off, and saturation characteristics. This approximation holds in practical feedback networks without low frequency cutoff. The photodetector is modeled as an ideal current source plus a shunt capacitance and a resistance. The amplifier is modeled as an ideal amplifier with an effective bandwidth limiting circuit in the input port. To consider the cut-off and the saturation charateristics of the feedback network, we introduce Fermi function.

Dynamics of the system can be described in terms of



(b)

Fig. 1 (a) Schematic diagram of the system.

(b) Equivalent circuit of the system. Ip is current generated by input photon, R_i is input resistance of the amp., R_d is incremental(ac) resistance of the photodetector, and C is sum of the diffusion capacitance of the detector and the equivalent input capacitance of the amp..

the normalized rate equations and an normalized equation for the feedback network[5,6]:

$$\dot{n} = i_b - i_f - (1-\epsilon s)(n-n_a)s - n,$$

$$\dot{s} = T_1[(1-\epsilon s)(n-n_a)s - s + \beta n], \qquad (2)$$

$$\dot{i} = T_2[c_1 s - i], \qquad (3)$$

where

$$i_f = i_s[1+e^{-(i-i_x)4A/i_s}]^{-1},$$

n and s are normalized electron and photon density of the active region of the diode laser, respectively. i is normalized input current of the amplifier. T_1 and T_2 are normalized photon lifetime and responce time of the feedback network with respect to carrier lifetime τ_s, $\dot{n} = dn/d\tau$, ϵ is normalized gain saturation coefficient, c_1 is normalized coupling efficiencies, $\tau = t\tau_s$, A is gain of the amplifier, β is spontaneous emission factor, i_s is is normalized saturation current, and i_x is normalized input current of the amplifier at the center of operation. The feedback is negative since the feedback current reduces the pump current of the diode laser. To understand steady state characteristics, first of all investigate graphical solution of the equations. We can get the following equation after ellimination of i and n in Eq.(1):

$$i_b - n_a - 1 - s_o = +i_s\,[1 + e^{-(c_1 s_o - i_x)4A/i_s}]^{-1}. \quad (4)$$

Graphical representation of above Eq.(4) is shown in Fig. 2. Here we neglected the effects of the gain saturation and the spontaneous emission. The zero intensity solutions are omitted in this paper. As seen in Fig. 2, only a single value of output exists at the given input parameters as can be seen in Fig. 2(a). We show the corresponding L-I curve of the device in Fig. 2 (b). The approximated cutoff current of the amplifier $i_c = i_x - i_s/2A$ are zero in Fig. 2 (a) and (b). The feedback reduces the output photon density if the amplifier acts in linear region and there are no effects in the cut off region. If amplifier acts in saturation region, actual injection current is $i_b - i_s$.

The stability of the steady state solutions can be determined by linear stability analysis. The characteristic equation is given by

$$\lambda^3 + \lambda^2[T_2 + 1 + s_o + \delta_1] + \lambda[T_2(1+s_o) + T_1 s_o + \delta_2] + T_1 T_2 s_o[1+g(A)] + \delta_3 = 0, \qquad (5)$$

where

$$g(A) = c_1 A/\cosh^2[2A(c_1 s_o + c_2 s_i - i_x)/i_s],$$

$$\delta_1 = T_1[\epsilon s_o + \beta(n_a+1)/s_o],$$

$$\delta_2 = -T_2 \epsilon s_o + T_1(\beta - \epsilon s_o^2) + \delta_1(T_2+1),$$

$$\delta_3 = T_1 T_2[\epsilon s_o - \beta(n_a-1)/s_o + (\beta - \epsilon s_o^2)(1+g(A))],$$

and λ is the eigenvalue. The function $g(A)$ is approximately unit if operation point of the amplifier is in linear region and it is nearly zero in cutoff or saturation region. Here the effects of the gain saturation and the spontaneous emission are considered. The steady state solution is stable if real parts of the all eigenvalues are negative and unstable otherwise. The stability of steady state solution is checked by using Routh-Hurwitz criteron.

There exists self-pulsing under the folloing condition:

$$\frac{(1+s_o)[s_o + (T_2+1+s_o)T_2/T_1] + (T_1 s_o + T_2^2)(\epsilon s_o + \beta(n_a+1)/s_o)}{T_2 s_o} < g(A), \quad (6)$$

and its oscillation frequency is

$$\omega_o^2 = (T_1+T_2)s_o + T_2 + \delta_2.$$

This is a surprising result since a negative feedback stabilizes the device. Physically this self-pulsing can be understood as an enhanced relaxation oscillation. If the photon density is increased by any chance, the electron density decreases as known in the relaxation oscillation and the feedback current increases. Thus, the pump or the injected electron density decreases since feedback is negative and the electron density decreases further. Through this process the relaxation oscillation is enhanced and selt-pulsing developes.

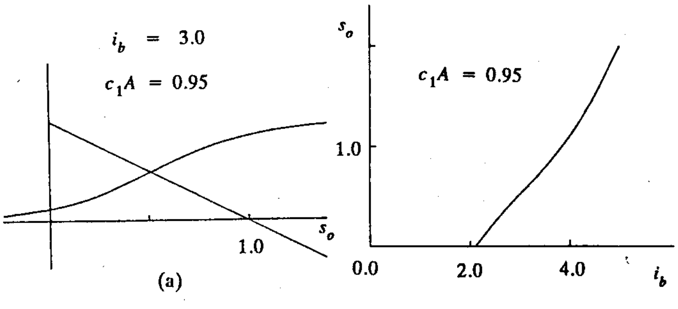


Fig. 2 Graphical solution and input-output curves at $n_a = 1$ and $i_s = 1$.
(a) Graphical solution with negative feedback.
(b) L-I curves.

The negative feedback reduces the damping factor of the relaxation oscillation and increases its frequency if the response time of the feedback network is faster than that of the carrier. And the self-pulsing develops in the limited range of the parameter T_2. The system goes to the stable region again if we increase T_2 further. The unstable region increases with increase of closed loop gain. Due to effects of the gain saturation and the spontaneous emission damping of the system increases and the region of the self-pulsing and the resonance peak in modulation response diminish. We show the dependence of unstable region on the closed loop gain and T_2 in Fig. 3. The unstable regions are inside of the curves. If response time of the feedback network is much faster than that of the carrier ($T_2 \gg 1$), the feedback current follows the photon density adiabatically. Thus dynamics of the system can be described by the rate equations. However, modulation bandwidth of the diode laser is wider than that of the solitary laser by the factor of $(1+c_1A)^{1/2}$. If $T_2 \ll 1$, the feedback network is responded to the time average of the photon density. Therefore there is negligible chage of the modulation characteristics from that of the solitary laser. The critical dependence of the damping factor on the feedback parameters can be used to study chaotic behavior. Since chaotic behavior in the directly modulated diode laser is very sensitive to damping of the system[7].

Now consider the large signal response of the device in the region of the self-pulsing. We show the simulated waveforms of the optical pulse, the carrier, and the input current of the feedback amplifier in Fig. 4. It is easy to expect that the pulse is formed by the through the following process. The photodetector convert the received optical pulse at a particular time to current pulse and it is fed to the diode laser. Due to finite response of the photodetector, the current pulse delayed. The current pulse reduces the pumping current of the diode laser and the optical pulse is terminated if the gain of the feedback amplifier is sufficient. Thus the pulse is located in the time interval of the actual delay time of the feedback network.

The dependence of the pulse width on the closed loop gain of the feedback loop is shown in Fig. 5 with various values of the steady state photons and the response time of the feedback network. The pulse width decreases as with increase of gain. However it saturates and increases finally. The saturation is arise from the limit of the obtainable pulse width due to the photon lifetime or cavity bandwidth. However the increase of the pulse width with increase of the gain comes from the finite dynarmic range of the feedback amplifier. As seen in Eq. (4), the operating point of the feedback amp. moves to saturation region if we increase the gain with fixed steady state photons. Thus, the effect of the feedback on the stability of the device decreases. This is reason of the decrease of the pulse width. The dependence of the pulse width on the gain of the feedback amp. decreases as response time of the feedback network increases. As seen in Fig. 5, the pulse width decreases with increase of the steady state photons. The typical pulse width is about 2 $10^{-2}\tau_s$ with several *GHz* repetition rates. We can obtaine less than 1.5 $10^{-2}\tau_s$ second pulse width under the optimum parameters. If the carrier lifetime of the diode laser is 0.5 nanosecond, the pulse width is 7.5 picosecond. This pulse width is less than that generated by active mode locking. However required bandwidth of the feedback network is about $10/\tau_s$ and closed loop gain of

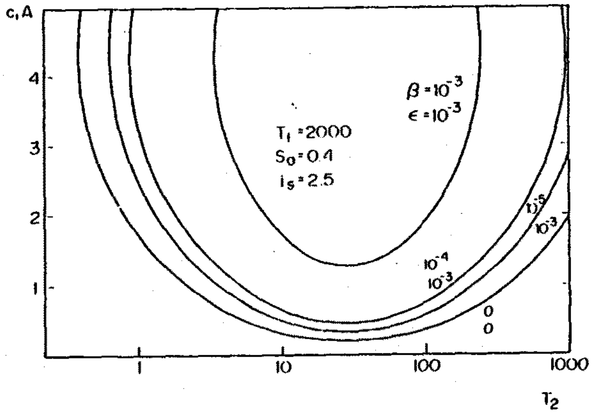


Fig. 3 The dependence of the unstable region on the closed loop and T_2.

the feedback network is about 3 which means the gain of the amplifier is about 20. This is easy to obtain by the monolithic integration of the device. The minimum pulse width can be generated by the diode laser with gain or loss switching is on the order of picosecond which is limited by the round trip time of the cavity. Thus minimum obtanable pulse width is limit by the intrinsic physical dynamics of the diode laser.

In conclusion we propose a new method of optical short pulse generation under the negative electro-optic feedback. The self-pulsing is induced by the feedback itself and pulse is formed by the interaction of the feedback signal and the dynamics of the diode laser. The simulated pulse width is on the order of picosecond with serval *GHz* repetition rates. By integrating the diode laser and photodetector with amplifier, one can improve the modulation charateristic of diode laser and can generate shorter optical pulses under the negative feedback. The attractive features of the proposed method are follows: it dose not need the modulation signal or critical optical alignment and low closed loop gain is sufficient to generate shortest pulse width.

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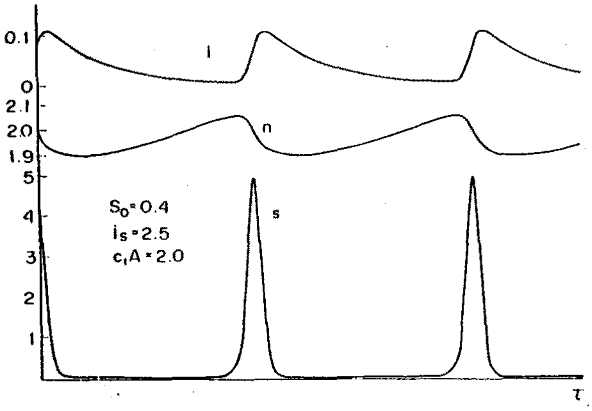

Fig. 4 Simulated waveform with s_0=0.4, i_s=2.5, c_1A=2, T_1=2000, T_2=10, $\beta=10^{-5}$, and $\epsilon=10^{-3}$.

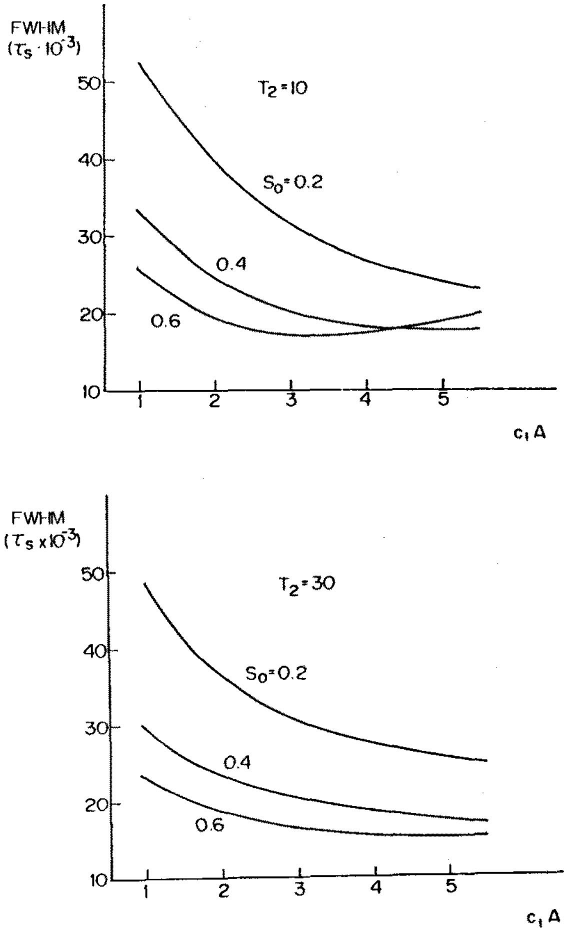

Fig. 5 Simulated pulse width vs. closed loop gain c_1A with the same parameters in Fig.4.