Improvement of the magnetizing inductance of a moving transformer integrated in the end teeth of a linear synchronous motor

Optical Neuron by Use of a Laser Diode with Injection Seeding and External Optical Feedback

Evert C. Mos, Jurgen J. L. Hoppenbrouwers, Martin T. Hill, *Associate Member, IEEE*, Martijn W. Blüm, Jean J. H. B. Schleipen, and Huig de Waardt

***Abstract*—We present an all-optical neuron by use of a multimode laser diode that is subjected to external optical feedback and light injection. The shape of the threshold function, that is needed for neural operation, is controlled by adjusting the external feedback level for two longitudinal cavity modes of the laser diode individually. One of the two modes corresponds to the output of the neuron, light injection at the wavelength of this mode provides excitatory input. Light injection in the other mode provides inhibitory input. When light corresponding to two input signals is injected in the same mode, summation of input signals can be achieved. A rate-equation model is used to explain the operating principle theoretically. The proposed injection seeding neuron is built using free-space optics to demonstrate the concept experimentally. The results are in good agreement with the predictions from the rate-equation model. Some experimental results show threshold functions that are preferable from a neural-network point of view. These results agree well with injection locking theory and experiments reported in literature.**

***Index Terms*—Hardware implementation, injection seeding, laser diodes, optical feedback, optical neural networks, optical telecommunications.**

I. Introduction

THE optical domain is attractive for hardware implementation of neural networks because of the high degree of parallelism that can be achieved in optical systems. An optical neural network was first presented by Psaltis and Farat [1]. Since then, optical implementation of neural networks has been the subject of many studies (for an overview see, e.g., [2] and [3]).

As pointed out by Jutamulia *et al.* [3], the threshold function needed for neural operation is realized in the electrical domain for most of the proposed optical neural networks. In this paper we describe a method to apply inputs and provide threshold operation in the optical domain. The threshold operation is implemented by use of the sensitivity of a multimode laser diode to external light injection. The threshold can be controlled by applying external optical feedback to the laser diode. The work presented here is closely related to the laser neural network (LNN) presented in earlier publications [4]–[6] in which we use external optical feedback to implement the threshold operation. As a result, the inputs in the LNN are in the optical transmission domain.

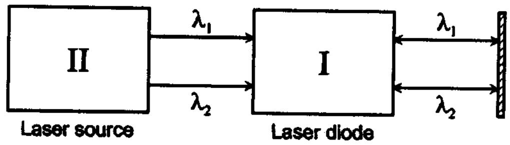

Fig. 1. Schematic drawing of injection seeding neuron concept. A laser diode I is provided with external optical feedback for two wavelengths (λ_1 and λ_2) to control the net optical gain at these wavelengths. By use of a tunable laser source II, light can be externally injected in laser diode I to switch the laser to one of the selected wavelengths.

With the work presented in this paper as well as with the LNN we aim at applications in optical telecommunications [6]. For this application area it is especially important to have all-optical neural operation. The inputs and outputs of such a neural network should preferably be in the optical power domain. The all-optical neuron presented in this work has inputs as well as output in the optical power domain.

The concept of the all-optical neuron is explained in Fig. 1 and relies on the injection of light from a source laser (II) into a laser diode (I). This technique, commonly known as injection seeding or injection locking is well documented [7]–[16] and has applications such as frequency conversion for telecommunication applications [11], [12]. In our optical neuron, we combine injection seeding and optical feedback to obtain neural-like operation. The laser that receives the injected light will represent a single neuron. This is in contrast with work on the laser neural network [4]–[6] where a single laser diode provides a multitude of neurons.

The principle of operation of the proposed injection seeding neuron is illustrated in Fig. 2. By use of controlled external optical feedback, laser diode I can only operate in one of two longitudinal modes. The figure shows conceptual drawings of the power spectra of the laser diode in two states. The left part of the figure shows the spectrum of the laser diode that is lasing in a certain mode 1, at wavelength λ_1, and corresponds to the state of our laser neuron without external light injection. Mode 2, corresponding to wavelength λ_2, is just below threshold and its optical power is defined as the output of our injection seeding

Manuscript received June 7, 1999.
E. C. Mos was with the Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands. He is now with ASM Lithography, 5504 DT Veldhoven, The Netherlands.
J. J. L. Hoppenbrouwers was with the Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands. He is now with Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands.
M. W. Blüm was with the Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands. He is now with Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands.
H. de Waardt and M. T. Hill are with the Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.
J. J. H. B. Schleipen is with Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands.
Publisher Item Identifier S 1045-9227(00)05879-3.

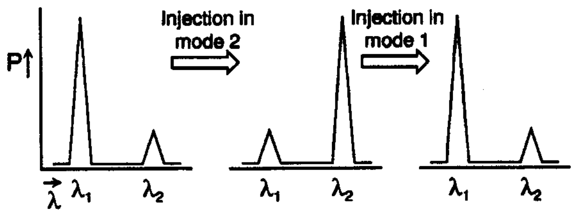

Fig. 2. Illustration of the operating principle of our injection seeding neuron. The left part of the figure shows the spectrum of a laser emitting at wavelength λ_1 (mode 1) without injection seeding. By injecting light in mode 2, the emission spectrum of the laser can be locked to λ_2, the output wavelength of the neuron. The output power at λ_2 will vary nonlinearly with the amount of injected power yielding neural-like behavior with an excitatory input. When the neuron is active, the laser emits at λ_2, as shown in the middle part of the figure. In this state, injection of light at λ_1 can force the laser back to emit at λ_1. Again a nonlinear, neural-like function is associated yielding an inhibitory input. The resulting state is shown in the right part of the figure.

neuron. Laser diode I can be made to emit this spectrum by carefully controlling the amount of external optical feedback for wavelengths λ_1 and λ_2.

If the source laser II operates at λ_2, and the amount of injected optical power is high enough, laser diode I will be locked to the injected light at wavelength λ_2. The power spectrum of the resulting state is shown in the middle part of Fig. 2. The optical power at wavelength λ_2, and thus the output of our injection seeding neuron, will vary nonlinearly with the amount of externally injected light at wavelength λ_2. It is this nonlinear response that is used to obtain neural-like action. The injected signal at wavelength λ_2 corresponds to an input signal of the neuron. From the preceding it is clear that this input signal causes the output of the neuron to increase and hence it is excitatory.

Inhibitory inputs can be obtained by injecting light at wavelength λ_1. Injection of light at this wavelength can cause laser diode I to go back to the original state where mode 1 dominates over mode 2 as drawn in the right part of Fig. 2. Again, a nonlinear, neural-like response is associated with the amount of injected light and the output power of the neuron. In the case of injection in mode 1 the input has a decreasing effect on the output of the neuron.

The shape of the nonlinear threshold function and the level of the threshold will depend on the amount of optical gain and losses of laser diode I at wavelengths λ_1 and λ_2. By controlling the external optical feedback conditions for laser diode I, the optical losses can be controlled for each wavelength of the laser diode independently. This can be used as a way to control and shape the threshold function of our injection seeding neuron.

Summation of inputs can be obtained by simultaneous injection of several optical input signals. Excitatory inputs should be injected at wavelength λ_2, inhibitory inputs at wavelength λ_1. Weights can be assigned to the inputs by attenuating the optical signals prior to injection into the laser diode.

The operating principle will be theoretically verified in Section II where we use a rate-equation analysis to model our laser diode with light injection and optical feedback. In Section III we present the experimental setup used to demonstrate the injection seeding neuron. The results are presented in Section IV and discussed in Section V. We conclude the paper in Section VI by giving recommendations for future work.

II. Theory

Injection locking of semiconductor lasers has been studied extensively in literature [7]–[16]. A laser diode can be locked to an externally injected signal if the wavelength of the injected signal is inside a wavelength range around a fundamental wavelength of the laser diode. The size of this locking range depends on the amount of externally injected power and the linewidth and power of the originally lasing mode.

A. Rate-Equation Analysis

In this section, we examine the combined effect of injection seeding and external optical feedback theoretically. To verify the concept of the injection seeding neuron, we model the laser as having two longitudinal modes with external light injection and external optical feedback for both of the modes.

As will be described in subsequent sections, the experimental injection seeding neuron consists of an antireflection (AR) coated laser diode that is coupled to an external cavity. However, for simplicity we model the system as a solitary laser diode with two longitudinal modes. The external reflectivity will be incorporated in the model as the effective reflectivity of the laser diode facet facing the external cavity. The simplified model is valid in our situation because the external cavity reflectivity is much larger than the residual reflectivity of the AR coated laser diode facet. In other words, the laser diode operates in the strong feedback regime [17].

The two longitudinal modes of the laser are labeled mode 1, and mode 2. As mentioned previously, the output of our neuron corresponds to mode 2 of the laser. Light can be injected in mode 1 and 2. The laser diode subjected to external light injection can be described by a set of rate equations [18] for the complex optical field and the number of carriers inside the active region.

To simplify the analysis we constrain the problem to externally injected light with a frequency that is inside the stable part of the locking range for both modes [13]. Furthermore we assume a constant phase difference between the externally injected optical field and the internal optical field. With these simplifications the photon phase can be omitted from the rate equation model and instead of the complex field equations we can use the equations for the photon number of the two modes. The photon number $P_m(t)$ of the two modes $m = 1, 2$ can be described with [18]

$$\frac{dP_m(t)}{dt} = (G_m - \gamma_m)P_m(t) + R_{sp} + 2k_c\sqrt{P_m(t)P_m^{inj}}. \quad (1)$$

The first term in the right part of (1) represents the net gain, where G_m is the wavelength dependent optical gain and γ_m is the photon decay rate for a mode. In this theoretical description we assume that both modes have approximately the same wavelength and thus experience the same optical gain, G. The second term in the right part of (1), R_{sp}, is the rate of spontaneous emission in mode m. Both gain and spontaneous emission are linear dependent on the carrier number [18].

In the injection seeding neuron, external feedback is used to control the net modal gain via the photon decay rate γ_m. For mode m we can write

$$\gamma_m = v_g \left(\alpha_{int} + \frac{1}{2L} \ln \left(\frac{1}{R_0 R_{ext,m}} \right) \right) \tag{2}$$

where v_g is the speed of light inside the laser material, α_{int} is the internal cavity loss and L the cavity length. R_0 is the facet reflectivity of the uncoated laser diode back facet and $R_{ext,m}$ is the effective facet reflectivity controlled by the external optical feedback for mode m.

External light injection is represented in the model by the injected photon number for mode m, P_m^{inj}. The coupling between the externally injected photons and the photons inside the active region is accounted for by a coupling constant k_c [18].

The rate equation model is completed with an equation for the carrier number $N(t)$ given by

$$\frac{dN(t)}{dt} = \frac{I}{q} - \gamma_e N(t) - \sum_{m=1}^{2} G_m P_m(t). \tag{3}$$

The first part of the right-hand side of (3) accounts for the electrically injected carriers in the active region, the second part for the spontaneous carrier decay and the third part for the stimulated carrier decay.

In this section we are concerned with finding the laser output power in the two modes as a function of the power injected into one (or both) of the modes. We now define this nonlinear function of output power versus externally injected power as the threshold function for the laser. This threshold function can be found from the steady-state solution of the rate equations (1) for modes $m = 1, 2$ and (3). The steady solution can be found by solving the following equations for N, P_1, and P_2:

$$(G - \gamma_1)P_1 + R_{sp} + 2k_c\sqrt{P_1 P_1^{inj}} = 0 \tag{4}$$

$$(G - \gamma_2)P_2 + R_{sp} + 2k_c\sqrt{P_2 P_2^{inj}} = 0 \tag{5}$$

$$\frac{I}{q} - \gamma_e N - G(P_1 + P_2) = 0. \tag{6}$$

B. Numerical Simulations

Let us first consider injection of light in mode 2 to verify excitatory input. The output of the neuron versus injected photon number in mode 2 is shown in Fig. 3 for different values of $R_{ext,2}$. The figure shows two threshold functions with reflectivity $R_{ext,2}$ set to 30% (a) and 25% (b). The laser diode back facet reflectivity for both modes, R_0, was set to 32%, which is the reflectivity for the uncoated laser diode facet. The front facet reflectivity for mode 1, $R_{ext,1}$, was arbitrarily set to same value. As can be seen from Fig. 3, increasing the injected light power causes mode 1 to be switched off and mode 2 to start lasing, as expected. Note that for a lower external reflectivity for mode 2, more power is required to switch the laser from mode 1 over to mode 2. This can be used to control the shape of the threshold function. The slope of the threshold function decreases with decreasing $R_{ext,2}$.

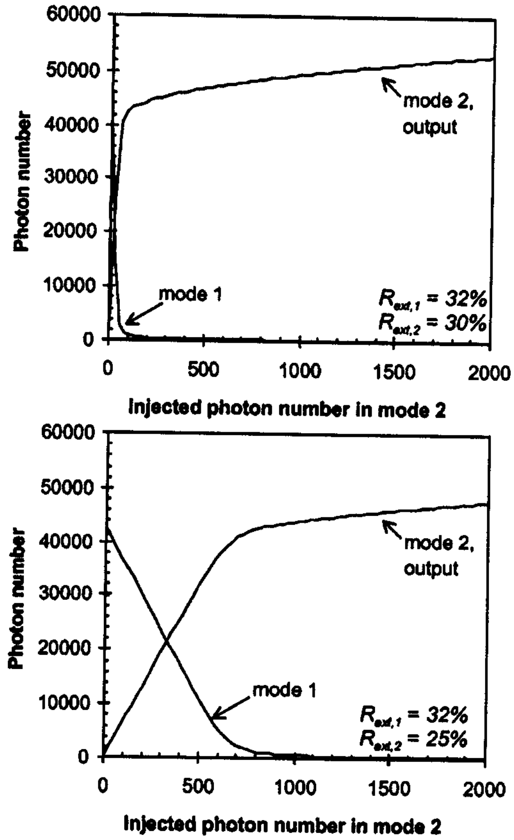

Fig. 3. Simulation results of the photon number in the two modes, 1 and 2, as a function of injected photon number in mode 2. The optical losses for mode 2 is lower in the top then it is in the bottom. In the top, $R_{ext,2} = 30\%$, in the bottom, $R_{ext,2} = 25\%$. Both Figs. show a nonlinear relation between the amount of injected photons in mode 2 and the photon number of mode 2, the output of our proposed neuron.

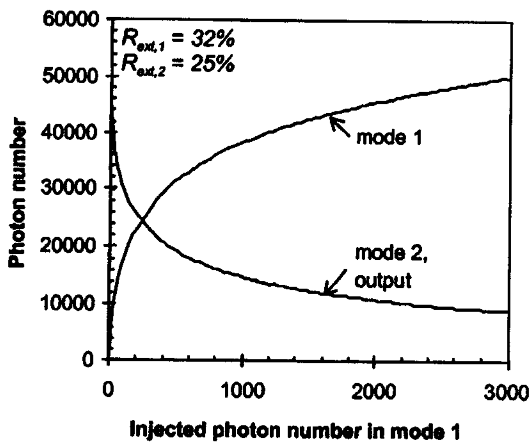

Fig. 4. Simulation results of the photon numbers in two modes, 1 and 2, as a function of injected photon number in mode 1 with a constant injection of 1200 photons in mode 2. The photon number of mode 2 is a nonlinear, decreasing function of the number of injected photons in mode 1.

The results presented in Fig. 4 demonstrate an inhibitory input signal. A constant amount of photons, 1200 in our simulations, is injected into mode 2, so that mode 1 is initially turned off

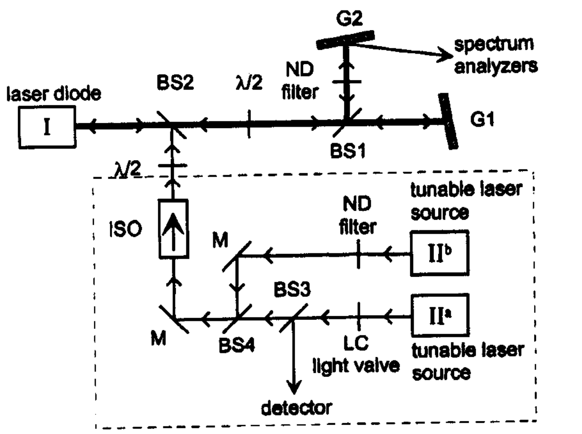

Fig. 5. Experimental setup to demonstrate the proposed injection seeding neuron. Laser diode I is coupled to two external cavities, wavelength tunable by use of gratings G1 and G2. A neutral density filter, ND controls the feedback efficiency for one cavity. Light from two continuously tunable laser sources II^a and II^b is injected via a beam splitter, BS2, and an isolator, ISO. Light from laser source II^a can be variably attenuated by use of a liquid-crystal (LC) light valve, and monitored via BS3 with a photodiode detector. A neutral density filter attenuates the light from laser source II^b by a fixed amount. $\lambda/2$-plates are inserted to match polarization states for optimum optical throughput.

and the laser is in the state corresponding to the middle part of Fig. 2. To turn mode 1 on again light is injected into mode 1, the inhibitory input. The results were obtained with $R_{ext,2}$ at 25% and $R_{ext,1}$ set to 32%. Due to the constant injection in mode 2, this mode does not switch off completely.

In order to relate the results of this section to the experimental results, it should be noted here that the photon number is directly proportional to optical power. From Figs. 3 and 4 it can be seen that injection of about 1% of the optical power is sufficient to switch the laser between modes 1 and 2.

III. Experimental Setup

In order to experimentally verify the concept of the all-optical neuron, a laser diode is needed with controllable optical feedback and external light injection for at least two longitudinal modes.

A. Optical Feedback

A setup is shown in Fig. 5. It consists of a laser diode (laser diode I, Uniphase CQL806, $\lambda \approx 680$ nm) coupled via a beam splitter, BS1, to two external cavities, one for each mode. For each cavity, the first-order reflection of a diffraction grating (G1 and G2, 2400 l/mm) is coupled back into the laser. The optical feedback is wavelength selective in this way and gratings G1 and G2 are tuned to wavelengths λ_1 and λ_2 corresponding to modes 1 and 2.

The exit facet of the laser diode facing the external cavity is provided with an antireflection coating with a residual reflectivity of approximately 5×10^{-4}. If the external optical feedback is sufficiently high, laser action will be dominated by the external cavity instead of the internal cavity of the laser diode [17]. Consequently, the laser will oscillate at the wavelength selected by the external cavity with the highest reflectivity. Neutral density filters can be inserted in the external cavity corresponding to G2 to set the amount of optical feedback for this cavity. The laser is temperature stabilized to prevent thermal drift of the mode wavelengths. A $\lambda/2$ plate is inserted to tune the polarization angle for optimal reflection at the gratings.

B. Light Injection

The output of two tunable laser sources II^a and II^b (Sacher Lasertechnik TEC500 series) is injected in the external cavity laser diode via a beam splitter (BS2). An isolator is used to prevent coupling of the light from the laser diode I to the tunable laser sources. A $\lambda/2$ plate is added to match the polarization state of injected light to that of the laser diode. For one source, II^a, the amount of injected power is made continuously variable by use of a liquid crystal light valve. With a photodiode detector we measure the amount of injection from this source. We can set the amount of injected power from the second source, II^b, to discrete values by use of neutral density filters. The amount of injected power from this source is measured by inserting a photodiode detector in the light path (not shown in the figure).

The wavelength of the injected light must be inside the locking range, that increases with decreasing cavity length [7], [9], [10]. For this reason, the external cavities are kept as short as possible. The resulting locking range is estimated at ~10 MHz. The wavelength stability of the tunable laser sources is within this range with unchanged drive current. Controlling the amount of injected light by changing the drive current of the tunable laser diodes would cause an unacceptable wavelength change.

C. Measurements

To monitor the spectral behavior of the laser diode I, the 0th order reflection of one of the gratings is directed to two spectrum analyzers. An optical multichannel analyzer (OMA) is used to measure the output spectrum of the laser at a coarse wavelength scale (resolution 0.25 nm, range 26 nm). This analyzer is used to measure the output power in the modes of the laser diode. The laser spectrum is also monitored at a finer scale by a Fabry Perot etalon (resolution 10 MHz, free spectral range 1.5 GHz), to verify whether the laser is lasing at a single external cavity mode.

With the setup of Fig. 5, the threshold functions can be measured by monitoring the output power in the two external cavity modes of laser diode I (via the OMA) while the amount of power injected by laser source II is varied. Since both injection sources, II^a and II^b, can be tuned to either one of the modes at λ_1 and λ_2, excitatory and inhibitory inputs as well as the adding of input signals can be experimentally demonstrated.

IV. Experimental Results

With the setup described in Section III, the threshold functions predicted by theory are experimentally verified. In all measurements presented in this section, the wavelength separation between the two modes was about 1.5 nm to ensure equal gain for the modes. The driving current of the laser diode was in the range of 60 to 70 mA. The total optical output power of the laser diode at this driving current measured ~5 mW.

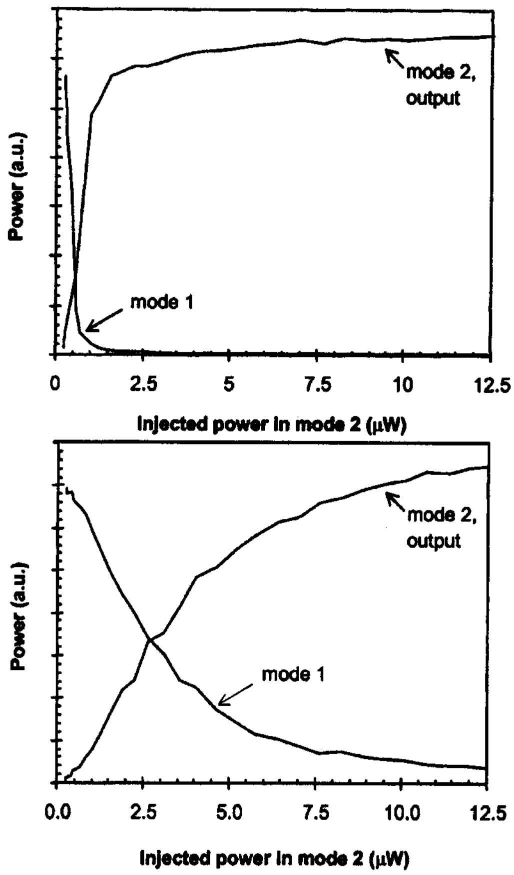

Fig. 6. Measured optical power in the two selected modes as a function of injected optical power in mode 2. (Top) Without neutral density filter; (Bottom) with neutral density filter. The power of mode 2 increases nonlinearly with increasing injection power in this mode. The power in mode 2 increases more rapidly as a function of injected power without the neutral density filter (compare Fig. 3).

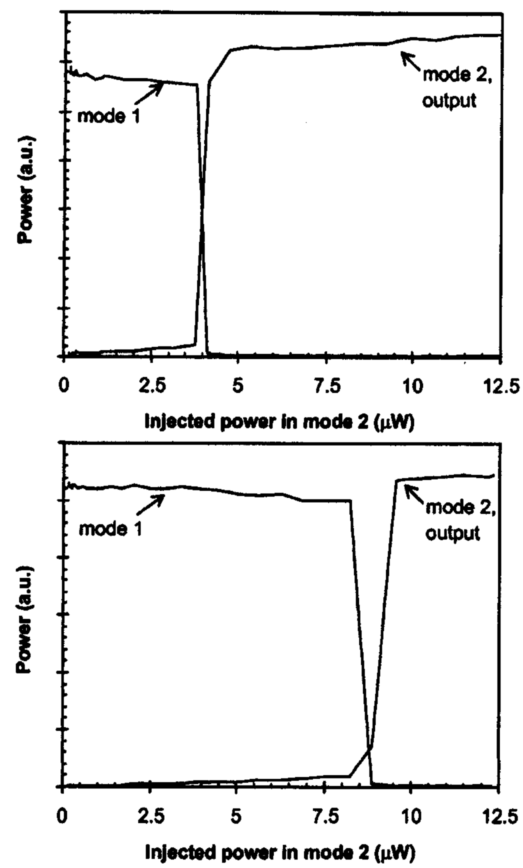

Fig. 7. Same as Fig. 6, but with a slight wavelength detuning of the injected signal. Much steeper threshold functions can be observed. More power is needed to switch the active mode.

A. Excitatory Input

In a first experiment an excitatory input is demonstrated. By controlling the feedback for both modes, mode 1 is made to lase in the absence of injected power. Next, light is injected at the wavelength corresponding to mode 2 with tunable laser source II^a only. The results are shown in Fig. 6. The amount of power injection in mode 2 is gradually increased from 0 μW to about 15 μW. The figure shows two nonlinear functions for different levels of the external feedback efficiency for mode 2. In Fig. 6(bottom) the feedback level for mode 2 is approximately a factor of 2 lower than that in Fig. 6(top). The figure shows the basic threshold function as well as the possibility to change the shape of the threshold function.

In the measurements corresponding to Fig. 6, the wavelength of the injected signal was adjusted to obtain optimal injection locking. If the wavelength is slightly changed ($\sim$10 MHz) from this optimal wavelength, different results are obtained. These results are shown in Fig. 7 where much steeper threshold functions can be observed. Compared to the measurements of Fig. 6, more injected power is needed to switch on mode 2.

B. Inhibitory Input

To demonstrate inhibitory inputs, the laser is first made to lase at wavelength λ_1 by setting the external reflectivity for the two modes 1 and 2. Now, 25 μW of optical power is injected in mode 2 by use of tunable laser source II^b. As a result, the laser oscillates at wavelength λ_2 as is expected. Fig. 8 shows the optical powers in both modes when power is injected in mode 1 by use of tunable laser source II^a with simultaneous constant injection in mode 2. If sufficient power is injected in mode 1, the laser switches to this mode and the power of mode 2 decreases.

Again, the experiments were repeated with a slight detuning of the injection source wavelength (laser source II^a). The results, presented in Fig. 9, show a much sharper threshold function.

C. Input Summation

To demonstrate the summation of two input signals we tuned both laser sources II^a and II^b to wavelength λ_2 corresponding to mode 2. By controlling the external feedback, mode 1 at λ_1 was made to lase.

First we measured the threshold function with injection by laser source II^a only. The results are represented by the drawn

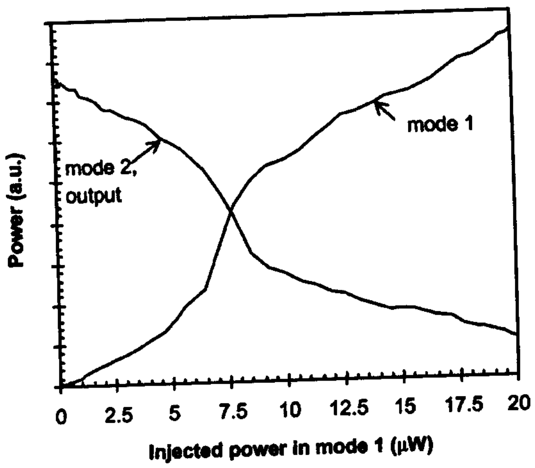

Fig. 8. Measured optical power in the two selected modes as a function of injected optical power in mode 1 with a constant injection of 25 μW in mode 2. The power in mode 2 shows a nonlinear decrement as a function of light injection in mode 1 (compare Fig. 4).

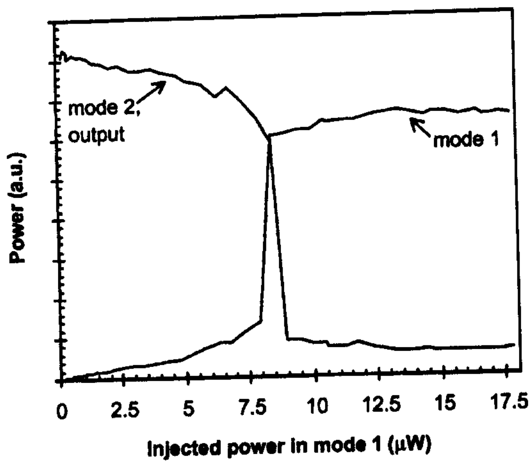

Fig. 9. Same as Fig. 8. but with a slight detuning of the injected signal in mode 1. A much steeper threshold functions can be observed.

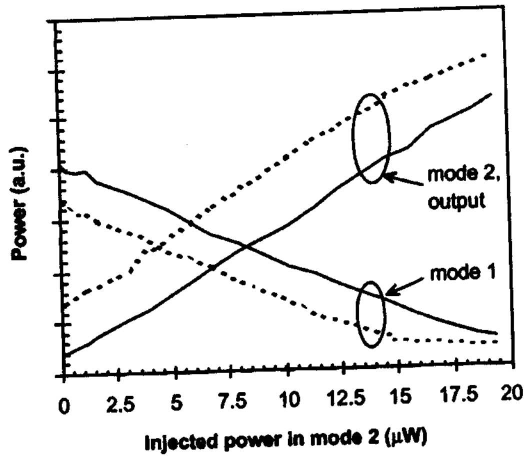

Fig. 10. Measured optical power in the two selected modes as a function of injected optical power in mode 2 (II^a) with and without a constant injection of 5.6 μW in mode 2 II^a. The drawn lines correspond to the measurements without the addition al injection, the dotted lines to the measurements with the additional injection. The dotted lines can be considered a shifted version of the drawn lines.

lines in Fig. 10. Next, laser source II^b is used to inject an additional 5.6 μW in mode 2. Again the amount of power injected with laser source II^a is varied and the optical power in the two modes is measured. The results are plotted with dotted curves in Fig. 10. The dotted lines can be considered a leftward shifted version of the drawn lines. The shift is due to the extra injection into mode 2 and is $\sim$4 μW. Note that only the linear part of the threshold curve is visible. This is due to the fact that the amount of losses for mode 2 were higher then those in the measurements presented in Fig. 6.

V. Discussion

A. Basic Neural Operation

The experimental results on the excitatory and inhibitory input, presented in Figs. 6 and 8, are in close agreement with the theoretically predicted curves of Figs. 3 and 4. The results of simulations and experiments demonstrate that the output of our proposed injection-seeding neuron exhibits neural-like behavior as a function of injected optical power. The shape and the level of the threshold can be varied by changing the amount of optical feedback for the two modes of the laser diode.

The ratio between the neuron output power and the injected optical power was about 10^3 in the measurements. In the simulations this ratio was about 10^2. This discrepancy can be due to differences between the used laser parameters, obtained from literature [18], and the actual laser parameters for our laser diode. Also the estimated optical feedback level and coupling efficiency will differ from the actual parameters.

B. Steep Threshold Functions

More discrepancy can be observed between the simulation results of Figs. 3 and 4, and the results presented in Figs. 7 and 9. The measured threshold functions have a much steeper transition region than the simulated ones. The measured results presented in these figures were obtained with a slightly detuned injection source. We believe that the differences are caused by this detuning and the shape of the locking region. The locking range, in this context, is the area in the detuning—injected power plane in which the laser locks to the injected signal. Various shapes of the locking range have been reported [9], [10], [13], [14]. Fig. 11 shows a schematic drawing of one of the reported shapes for the locking range (after [13]). The curves in the figure represent the edges of the locking range. The area within the solid lines is the stable locking range, the area between the solid line and the dashed line is the unstable locking range.

In our theoretical model we assume that light is injected within the locking range of the laser diode. This proved to be a valid assumption for the measurements of Figs. 6 and 8. Hence, the trajectory of the light injection corresponding to these figures can be represented by arrow A in Fig. 11. When, however, the frequency of the injection source is detuned, as was the case for the measurements presented in Figs. 7 and 9, the injection is not always inside the locking range. This situation is indicated with trajectory arrow B in Fig. 11. Now, the locking range is only reached when the power exceeds a

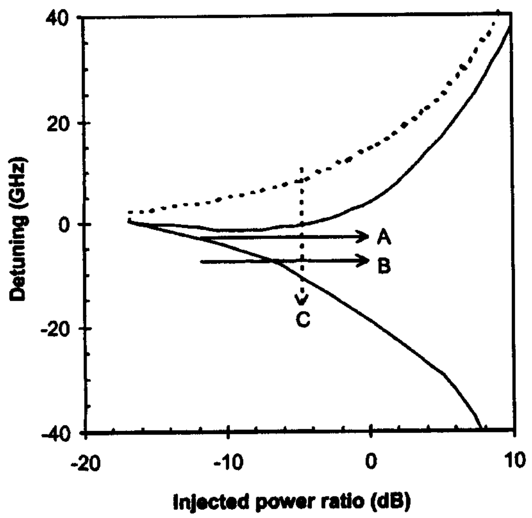

Fig. 11. Plot of frequency difference between injected signal and free running signal of a laser diode showing various locking ranges (after [13]). Stable locking occurs in the range within the solid lines. The area between the dashed and the solid line corresponds to the unstable locking range. Solid arrows indicate measured trajectories. Arrow A corresponds to Fig. 6, arrow B to Fig. 7. The dotted arrow C is the trajectory of [7], [15], [16].

certain value. This explains why more injected power is needed to switch the active mode of the laser.

The sharp transition in the laser output power from the unlocked to the locked condition on this side of the locking range was already reported by a number of groups [7], [15], [16]. These groups investigated the locking properties of injected light having a varying optical frequency as indicated by the dotted trajectory arrow C. They explain the sharp transition by the carrier induced refractive index change caused by the injected signal.

From a neural-network point of view, the experimentally obtained threshold functions of Figs. 7 and 9 are preferable to the experimental results of Figs. 6 and 8 and the theoretically predicted curves of Figs. 3 and 4. A smaller change in externally injected light is needed in the results of Figs. 7 and 9 to switch the neuron from an inactive to an active state. As the amount of injected light corresponds to the weighted sum of inputs of our proposed neuron, a higher number of inputs would be possible with the threshold functions of Figs. 7 and 9. Furthermore, the shape of the threshold function of Figs. 7 and 9 is closer to a sigmoid (S-like) shape that is commonly used in neural networks [19].

C. All-Optical Bipolar Inputs

As demonstrated both in theory and experiment, excitatory as well as inhibitory inputs are possible with our conceptual all-optical neuron by simply injecting the input signals at selected wavelengths. In other optical neural networks, inhibitory inputs are usually implemented by electronic subtraction (see, e.g., [1], [20]–[22]). The advantage of our approach is that no conversion from the optical to the electrical domain is necessary. Another all-optical way of implementing bipolar inputs uses interferometrical methods [23]. This method requires a high level of optical coherence and mechanical stability.

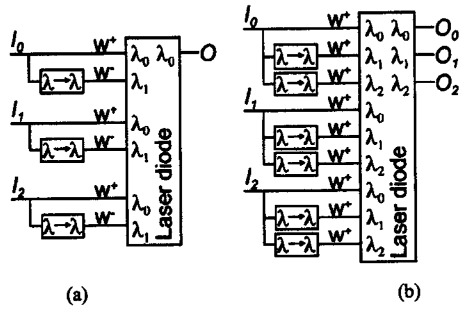

Fig. 12. Conceptual drawing of injection seeding neuron with some connections. (a) With a number of weighted inputs and one output. Wavelength converters ($\lambda \rightarrow \lambda$) are used to copy the input signals at λ_0 to λ_1 in order to provide excitatory as well as inhibitory weighted (w^+ and w^-) input signals. (b) Injection seeding neuron with a number of weighted inputs and a number of outputs. The input signals are copied to a $\lambda_0 \cdots \lambda_2$ corresponding to outputs $O_0 \cdots O_2$. The wavelength with the highest sum of weighted (w^+) inputs will be the only one lasting, resulting in a winner-take-all neural network.

Although both phase and frequency of the two injection sources were not exactly equal in our experiment, summation of input signals by simultaneous injection is demonstrated. A 5.6 μW additional injection by a second source shifted the neural response by 4 μW. Although the addition is not exact (a shift of 5.6 μW would be expected), for neural operation it is quite adequate as the neural weights can be adapted to equalize the effect of each input signal. The results indicate that the two injection signals do not need to be coherently added to obtain summation. This eases the constraints on the design of an all-optical neuron constructed from a number of injection seeding neurons. The signals, however, need to be injected inside the locking range of the laser diode.

In our laser neural network [4]–[6] the inputs are implemented in the optical transmission domain. A single layer neural network is realized with just one laser diode. In the all-optical neuron presented in this paper, the inputs are transferred to the optical power domain which is advantageous for the application area of optical telecommunications.

D. Optical Neural Network

To build a neural network, a number of injection seeding neurons should be interconnected. In Fig. 12(a), a single injection seeding neuron with a number of connections is depicted. An input signal can either come from outside of the network or from a another injection seeding neuron in the neural network. Because in a general neural network both positively (w^+) and negatively (w^-) weighted inputs are required, the input signals $I_0 \cdots I_2$ at λ_0 are copied to wavelength λ_1 by means of a set of wavelength converters (See, e.g., [11] and [12]). As presented in this paper the light at λ_0 and λ_1 can be used to provide excitatory and inhibitory input signals to an injection seeding neuron operating at λ_0. This output signal of the neuron, O, can serve as an input signal for other neurons to form a neural network. The weighted interconnection between the injection lasers in the network can be achieved by use of a free-space optical matrix vector multiplier [24] for each layer of the neural network. Any network topology is possible with this concept.

Alternatively, other wavelengths of the laser diode could be used to form a neural network with just one laser diode. This is shown schematically in Fig. 12(b). Now, all the input signals are copied to a number of wavelengths $\lambda_0 \cdots \lambda_2$ corresponding to output signals $O_0 \cdots O_2$. The resulting signals can be used to provide excitatory inputs for the corresponding output. Due to mode competition only the wavelength with the highest amount of summed excitatory input will lase, suppressing laser action at any other wavelength. Thus the resulting neural network will be limited to a winner-take-all network that closely resembles the laser neural network presented in earlier work [4]–[6].

Applications of the proposed all-optical neural network are envisioned in data processing for the field of optical telecommunications. An example is the header processing task in a network switch of a packet switched telecom network (see also [6]). For such applications sufficient operation speed and functional complexity are required. The speed of the injection locking concept is already demonstrated to be compatible with the field of optical telecommunications [11], [12]. The functional complexity of the proposed winner-take-all injection seeding neural network is expected to be equal to that of the laser neural network. With the laser neural network we already demonstrated training of functions toward the packet switching task. [6].

The injection seeding neuron, presented in this paper consisted of a laser diode with controlled optical losses for two modes. The controlled losses do not necessarily have to be implemented with an external cavity setup. From a practical point of view and considering the size of the locking range, it is preferable to come to a compact, integrated optics, injection seeding neuron.

VI. Conclusions

We have presented all-optical neural operation by use of light injection in a laser diode. External optical feedback is used to control the shape of the threshold function. By injecting light at different wavelengths excitatory as well as inhibitory inputs are possible with this concept. Summation of input signals can be achieved by simultaneous injection of different input signals at the same wavelength.

The injection seeding neuron is theoretically demonstrated by use of a rate-equation model. An experimental setup is used to confirm the operating principle of the proposed all-optical neuron. We demonstrated basic threshold operation, excitatory and inhibitory inputs as well as summation of input signals with the experimental setup. The numerical results, predicted by the model are in good agreement with the measurements. Under certain injection conditions, a threshold function is observed that is preferable for neural operation. These results were obtained with a detuned injection frequency and can be explained by considering the shape of the injection locking range.

To examine the feasibility of the all-optical neuron, it will be necessary to build a (modest size) neural network. In such a neural network the interconnection of neurons and the weighting of these connections needs to be tested. Connecting the output of one injection seeding neuron to the input of another injection seeding neuron will require a certain level of wavelength stability of the external cavity laser diodes as the characteristics of the injection seeding neurons depend on the injected wavelength. The level of wavelength stability should be investigated before starting experiments on a neural network.

For the proposed application area of optical telecommunications, it is of great importance that the operation speed of the neural network is sufficiently high. Although previous work indicates the possibility of using injection seeding for telecom applications, this issue should be addressed in future work.

References

[1] D. Psaltis and N. Farat, "Optical information processing based on an associative-memory model and neural nets with thresholding and feedback," *Opt. Lett.*, vol. 10, pp. 98–100, 1985.

[2] H. J. Caulfield, J. Kinser, and S. K. Rogers, "Optical neural networks," *Proc. IEEE*, vol. 77, pp. 1573–1583, 1989.

[3] S. Jutamulia and F. T. S. Yu, "Overview of hybrid optical neural networks," *Opt. Laser Technol.*, vol. 28, pp. 59–72, 1996.

[4] S. B. Colak, J. J. H. B. Schleipen, and C. T. H. Liedenbaum, "Neural network using longitudinal modes of an injection laser with external feedback," *IEEE Trans. Neural Networks*, vol. 7, pp. 1389–1400, 1996.

[5] E. C. Mos, J. J. H. B. Schleipen, and H. de Waardt, "Optical mode neural network by use of the nonlinear response of a laser diode to external optical feedback," *Appl. Opt.*, vol. 36, pp. 6654–6663, 1997.

[6] E. C. Mos, J. J. H. B. Schleipen, H. de Waardt, and G. D. Khoe, "Loop-mirror neural networking using a fast liquid-crystal display," *Appl. Opt.*, vol. 38, pp. 4359–4368, 1999.

[7] R. Lang, "Injection locking properties of a semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 976–993, 1982.

[8] N. Schunk and K. Petermann, "Noise analysis of injection-locked semiconductor injection lasers," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 642–650, 1986.

[9] I. Petitbon, P. Gallion, G. Debarge, and C. Chabran, "Locking bandwidth and relaxation oscillations of an injection-locked semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-24, pp. 148–154, 1988.

[10] F. Mogensen, H. Olesen, and G. Jacobsen, "Locking conditions and stability properties for a semiconductor laser with external light injection," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 784–793, 1985.

[11] S. Murata, A. Tomita, J. Shimizu, and A. Suzuki, "THz optical-frequency conversion of 1 Gb/s-signals using highly nondegenerate four-wave mixing in an InGaAsP semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 1021–1023, Oct. 1991.

[12] R. P. Braun, C. Caspar, H. M. Foisel, K. Heimes, B. Strebel, N. Keil, and H. H. Yao, "Transparent switching node for optical frequency division multiplexed signals," *Electron. Lett.*, vol. 29, no. 10, pp. 912–913, 1993.

[13] P. Debernardi, "Locking characteristics of Fabry-Perot semiconductor laser oscillators with side-mode injection," *Opt. Lett.*, vol. 21, no. 9, pp. 656–658, 1996.

[14] L. Li, "Static and dynamic properties of injection-locked semiconductor lasers—An overview," *IEEE J. Quantum Electron.*, vol. 30, pp. 1701–1708, Aug. 1994.

[15] C. H. Henry, N. A. Ollson, and N. K. Dutta, "Locking range and stability of injection lcoked 1.54 μm InGaAsP semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1152–1156, Aug. 1985.

[16] C. E. Moeller, P. S. Durkin, and G. C. Dente, "Mapping the injection-lock band of semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 25, pp. 1603–1608, July 1994.

[17] R. W. Tkach and A. R. Chraplyvy, "Regimes of feedback effects in 1.5 mm distributed feedback lasers," *J. Lightwave Technol.*, vol. LT-4, pp. 1655–1661, 1986.

[18] G. P. Agrawal and N. K. Dutta, *Long-Wavelength Semiconductor Lasers*. New York: Van Nostrand Reinhold, 1986.

[19] R. P. Lippman, "An introduction to computing with neural nets," *IEEE Acoust., Speech, Signal Processing Mag.*, vol. 4, pp. 4–22, 1987.

[20] M. Kranzdorf, B. J. Bibner, L. Zhang, and K. M. Johnson, "Optical connectionist machine with polarization-based bipolar weight values," *Opt. Eng.*, vol. 28, pp. 844–848, 1989.

[21] A. P. Ittycheriah, J. F. Walkup, T. F. Krile, and S. L. Lim, "Outer product processor using polarization encoding," *Appl. Opt.*, vol. 29, pp. 275–283, 1990.

[22] I. Shariv, O. Gila, and A. A. Friesem, "All-optical bipolar neural network with polarization-modulation neurons," *Opt. Lett.*, vol. 16, pp. 1692–1694, 1991.

[23] J. H. Hong, S. Campbell, and P. Yeh, "Optical pattern classifier with perceptron learning," *Appl. Opt.*, vol. 29, no. 20, pp. 3019–3025, 1990.

[24] J. W. Goodman, A. R. Dias, and L. M. Woody, "Fully parallel, high-speed incoherent optical method for performing discrete Fourier transforms," *Opt. Lett.*, vol. 2, pp. 1–3, 1978.

Evert C. Mos was born in Arnhem, The Netherlands, on December 9, 1968. He received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology in 1994. In September 1999, he received the Ph.D. degree in electrical engineering from the Eindhoven University of Technology. The topic of Ph.D. thesis was an optical neural network by use of the longitudinal modes of a laser diode. He studied the operation of this optical neural network and examined the capabilities of the neural network toward the application area of optical telecommunications.

In 1995, he joined the Faculty of Electrical Engineering at Eindhoven University. In November 1999, he joined the Measurement System Development Department, ASM-Lithography, Veldhoven, The Netherlands, where he is working as a Designer.

Jurgen J. L. Hoppenbrouwers received the M.Sc. degree in electrical engineering in 1998 from the Eindhoven University of Technology, The Netherlands. His graduation project was part of the work presented in this paper.

Currently, he is a Research Scientist at Philips Research, Eindhoven. His research interests include Plasma Display Electronics and Image Processing.

Martin T. Hill (S'96–A'97) was born in Sydney, Australia, in 1968. He received the B.E. degree (with first class honors) in 1990 and the M.Eng.Sc. degree in 1992 from the University of Western Australia, and the Ph.D. degree in 1997 from Curtin University of Technology, Perth, Western Australia.

During 1990, he was a Member of Technical Staff at QPSX Communications Pty. Ltd., and from 1993 to 1998, he worked at the Australian Telecommunications Research Institute. His work there included the design of high speed integrated circuits for high speed digital transmission networks. Since 1998, he has been with the Department of Electrical Engineering, Technical University of Eindhoven, The Netherlands, where he is involved in research on photonic components for optical packet switching.

Martijn W. Blüm received the M.Sc. degree in electrical engineering in 1997 from the Eindhoven University of Technology, Eindhoven, The Netherlands.

For his final thesis he worked on a Laser Neural Network. After his graduation he started working at Philips Research Laboratories in the field of optical recording.

Jean J. H. B. Schleipen received the M.Sc. degree in experimental physics in 1987 and the Ph.D. degree in 1992, both from the University of Nijmegen, The Netherlands.

He is a Research Scientist with Philips Research Laboratories, Eindhoven, The Netherlands. He is currently working in the field of diffractive optics and optical light-path geometries for future optical recording systems.

Huig de Waardt was born in Voorburg, The Netherlands, on December 1, 1953. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Delft University of Technology, Delft, The Netherlands, in 1980 and 1995, respectively.

In 1981, he joined the Department of Physics, KPN Research, Leidschendam, The Netherlands, where he was engaged into research on the performance aspects of long-wavelength semiconductor laser diodes, LED's and photodiodes. In 1989 he moved to the Department of Transmission, where he has been working int he fields of high bit-rate direct-detection systems, optical preamplification, wavelength division multiplexing, dispersion related system limitations, and the system application of resonant optical amplifiers. He contributed to (inter)national standardization bodies and to the EURO-COST activities 215 and 239. In October 1995, he was appointed as Associate Professor at the University of Eindhoven, Faculty of Electrical Engineering, in the area of high-speed trunk transmission. His current research interests are in applications of semiconductor optical amplifiers, high-speed OTDM transmission, integrated optical cross-connects, and WDM optical networking. He was active in European research programs as ACTS BLISS and ACTS Upgrade. At present, he is responsible for the WDM system demonstrator within the ACTS APEX project.