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A New MOSFET IC Laser-Driver With On-Chip Thermal and Optical Stabilization

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ABSTRACT. This paper presents a new more advantageous configuration for the laser diode that is used as the principle light source in optical fiber communications and a range of other applications. Most of the common drawbacks have been eradicated through the new design which is integrated through the well known floating gate MOSFET technology. Advantages including improved thermal and optical stabilization and easy direct modulation are realized from a new on-chip laser driver. Besides, the technique guarantees compensation for device leakage and device to device tolerances. The resulting device is cheaper and easy to construct.

The voltage control provides better output power modulation and improve linearity for high output power levels. The threshold current required to stimulate emission is also reduced to ~ 10^3 A/cm^2 at 300 K with an active region thickness of ~ 0.5 μm. In fact the proposed design provides a thinner well defined active region (0.3 μm) which also acts as an optical cavity resonator, besides satisfying the conditions for the confinement of charged carriers and optical fields.

Great efforts have been made, in the early 1970's, in research in optical communications and related areas. This resulted in significant technological advances in optical sources and led in turn to the birth of the semiconductor laser diode which is, now, the principal light source used for optical fiber communications. This device has adequate output power for a wide range of applications; its optical output can be directly modulated. It has a high efficiency and

its dimensional characteristics are compatible with the optical fiber. The major aspects of lasers, their constructions, and principles of operation are available in literature (Wilson and Hawkes 1983, Verdeyen 1981, Kressel and Butler 1977, El-Hennawy and Al-Ghamdi 1993, El-Hennawy *et al.* 1993).

The optical energy released from these devices has spatial and temporal coherence which means it is highly monochromatic ($\lambda \sim 0.1$ to 1 Å) and the output beam is very directional ($\theta_{\parallel} \sim 5°$ and $\theta_{\perp} \sim 30°$) (Verdeyen 1981, Kressel and Butler 1977, El-Hennawy *et al.* 1993). However, laser diodes are not easy to use without employment of complex drive circuitries and thermal and optical stabilization schemes (El-Hennawy and Al-Ghamdi 1992) which are expensive to realize and have relatively low yield (Kressel and Butler 1977, El-Hennawy *et al.* 1993).

In this paper we present a new MOSFET IC original configuration, to be integrated on the same chip with the laser source, to control and smooth up the output power level and stabilize the system against temeprature variation and aging. It also provides direct-modulation facility.

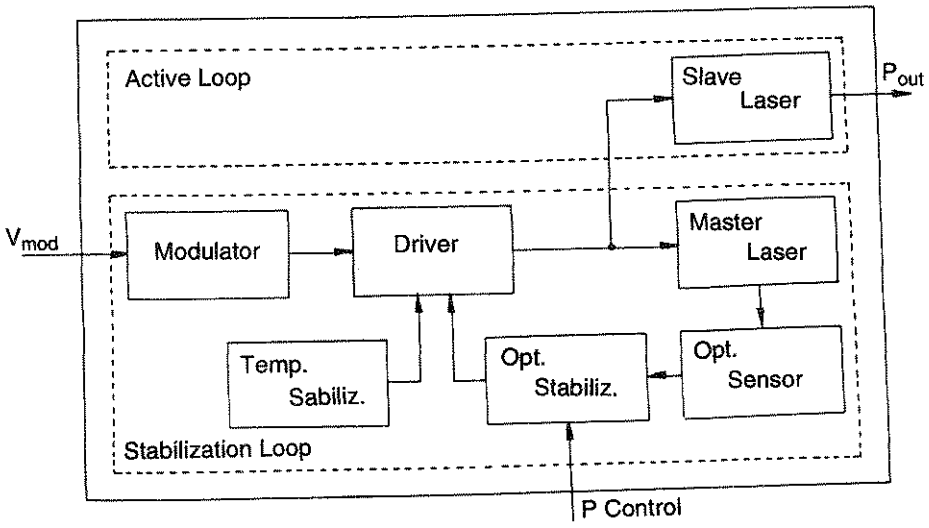

Fig. 1. Block diagram of proposed laser configuration.

1. Laser Source

Figure (1) shows the block diagram of the proposed laser configuration with on-chip thermal and optical stabilization, output-power level control and modulation. It is constructed of two basic loops; one is the active loop which contains the master laser and the thermal and optical stabilization circuitries. This loop is responsible for

giving two voltage signals, one is proportional to the output power level and the second is proportional to the operating temperature. These signals are fed through a negative feedback loop to the laser driver so as to smooth up the output power level and to compensate for the effects of the operating temperature variations and the device aging. Supplementary circuitries are introduced for controlling the output power level and allowing for modulation.

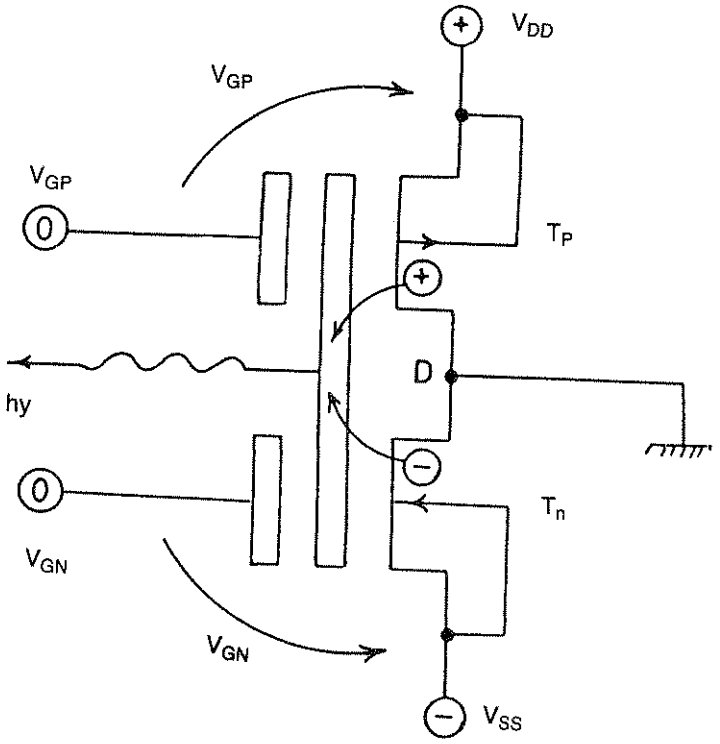

Fig. 2. MOSFET laser source structure.

1.1 *Laser MOSFET*

It is cosntructed, as shown in Fig. (2), with a floating gate CMOS inverted T_p and T_n whose floating gate is common for the two MOSFET's. A non doped GaAs compound (Wilson and Hawkes 1983, Verdeyen 1981, Kressel and Butler 1977, El-Hennawy and Al-Ghamdi 1992, El-Hennawy *et al.* 1993), is used, to realize the floating gate. The common drain D is carted while the sources of T_p and T_n are biased to V_{DD} and V_{SS} respectively ($V_{DD} = V_{SS} = 10$ V). The gates of T_p and T_n are biased respectively to V_{GP} and V_{GN} which should be equal ($V_{GP} = V_{GN} = 0$) in

absence of feedback (stabilization loop is disconnected). The channel length L, width Z, first oxide thickness (between the channel and floating gate) h_o and second oxide thickness (between the floating and control gates) h_I are 1 μm, 400 μm, 400 Å and 800 Å, respectively. To keep the floating gate potential V_{FG} as great as possible (greater value of $V_{FG} = V_{GP} = V_{GN}$) the technique shown in Fig. 3 is used. In this

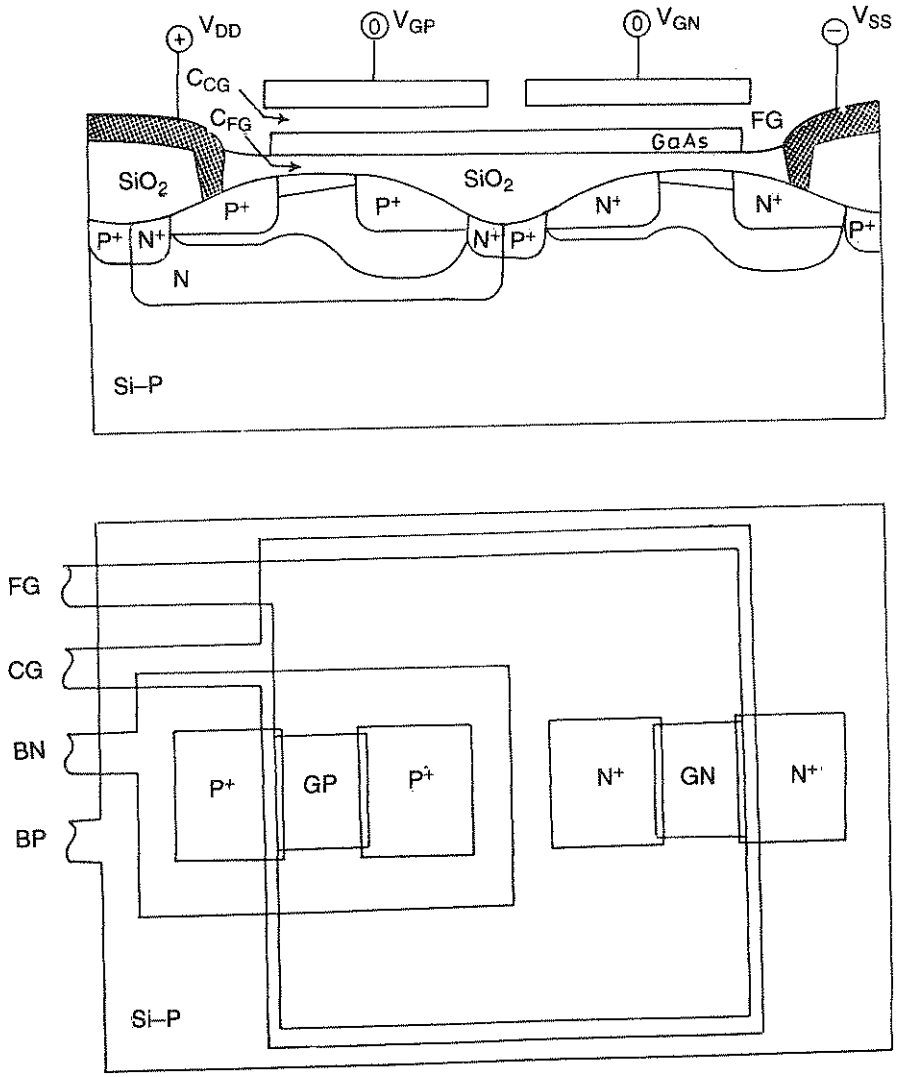

Fig. 3. Configuration to maximize floating gate potential.

case the overlapping area between the control and the floating gates is kept much greater than that between the floating gate and the channel. Hence the floating gate to control gate capacitance C_{CG} will be much greater than that existing between the floating gate and the channel C_{FG} (El-Hennawy 1992, El-Hennawy and Al-Ghamdi 1992).

The operation of the laser MOSFET is as follows; the drain-source voltages of T_p and T_n are sufficient to heat up the channel carriers and enables them to jump over the Si-SiO_2 interface barrier (El-Hennawy and Al-Ghamdi 1992, El-Hennawy and Mobarek 1993). Since the control gate of T_p is negative with respect to its source and that of T_n is positive with respect to its source, then hot holes and hot electrons are simultaneously injected into the floating gate. The design values of L and Z of T_p and T_n are modified so as to make the hot-hole current I_{gp} exactly equal to the hot-electron current I_{gn}. In this case the net floating-gate current $I_g = I_{gp} - I_{gn}$ is zero, regardless of the level of carrier pumping or power output, which means null floating-gate power dissipation. This will guarantee greater output power levels and better linearity. Also no charge builds up in the floating gate which keeps its potential $V_{FG} = 0$ and consequently sustains high carrier acceleration into it all the time. Also smaller losses and higher efficiency are expected due to better homogeneity of the floating gate material and no gate heating takes place because it is not doped (Wilson and Hawkes 1983, Verdeyen 1981, El-Hennawy *et al.* 1993).

The electrons and holes pumped into the GaAs floating gate recombine radiatively and release radiation energy $h\nu$ with ν being the radiation frequency determined by the energy gap E_g ($h\nu = E_g$). The floating gate is surrounded by highly clean SiO_2. It has a refractive index ($n_{or} = 1.4$) which is smaller than that of GaAs ($n_a = 3.6$) and an energy gap $E_g = 8.1$ eV which is greater than that of GaAs (1.43 eV) and thus it provides the desired dual confinement for charge carriers and optical fields and acts at the same time as an optical resonant cavity. Since the quantum transitions here occur between nearly discrete energy levels, then the radiation of the new device will have spatial and temporal coherence and will be highly monochromatic and highly directional ($\theta_{\parallel} \sim 5°$ $\theta_{\perp} = 30°$) and $\lambda \sim 0.1 - 1$ Å). In addition, the floating gate thickness is very small (~ 0.3 μm or less) which increases the fraction of radiative recombination and decreases the absorption of the emitted radiation by the active region it-self (Wilson and Hawkes 1983, El-Hennawy *et al.* 1993).

The output power is given by (Wilson and Hawkes 1983):

$$P_o = ZL\,(J_g - J_{gth})\,\eta_i\,\frac{h\nu}{q}\,\frac{\left(\frac{1}{2Z}\ln\frac{1}{R_1R_2}\right)}{\left(\gamma+\frac{1}{2Z}\ln\frac{1}{R_1R_2}\right)};\quad J_g > J_{gth}$$

$$J_{th} + \frac{8\pi\nu_0^2 q t\;\nu n^2}{\eta_i C^2}\left(\gamma+\frac{1}{2Z}\ln\frac{1}{R_1R_2}\right)$$

With: q the electron charge (1.6×10^{-19} C)

t the floating gate thickness ~ 0.3 μm

η_i internal efficiency

Z the floating-gate width

R_1, R_2 the reflectivities of the floating gate internal surfaces.

ν line width

γ loss efficiency

1.2 *Design Considerations*

The MOSFET channel length L = 1 μm or less is experimentally suitable for offering the carrier heating required to give a hot carrier gate current density which is greater than the threshold value (~ 562 A/m^2) needed for lasing (El-Hennawy and Al-Ghamdi 1992, El-Hennawy and Mobarek 1993). The channel width Z (which represents the active region length) is taken 400 μm which is much greater than both the active region width (10 μm) and thickness (0.3 μm) to guarantee a limited number of modes (El-Hennawy 1992, Shahab and El-Hennawy 1990) and therefore, results, in smaller losses and modal noise, and gives better coherence and directionality and improves the device reliability (Wilson and Hawkes 1983, El-Hennawy *et al.* 1993). The HMOS II technology design rules are used.

2. Laser Driver

It consists, as shown in Fig. 4, of a differential input stage T_2, T'_2 which is biased and loaded with current sources T_2, T'_2. A common mode feedback technique

is inserted using T_3, T_4 and T_5 to stabilize all node voltages and branch currents against ambient temperature variations and circuit aging (El-Hennawy and Shahab 1990). The difference amplifier is designed so as to give $V = 0 = V'_0$ in the absence of feedback and modulating signals. It has a difference mode gain of 200, and input offset voltage of about 2 mV and voltage drift of 20 μV/°C. These characteristics are sufficient for our applications.

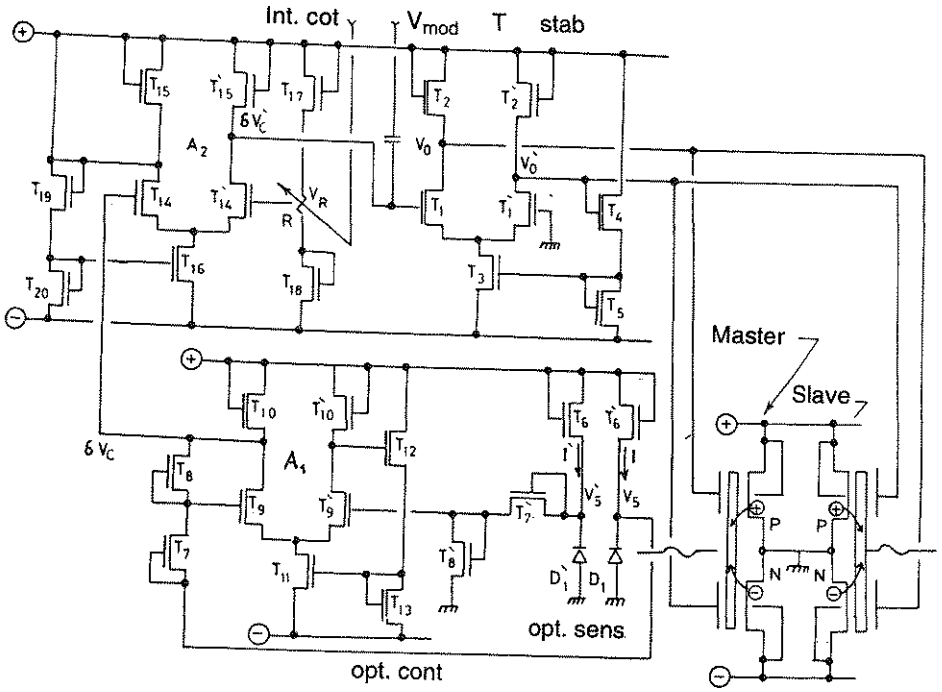

Fig. 4. Laser driver circuit configuration.

2.1 *Radiation Level Monitoring*

It is composed of two branches, the first (T_6, D_1) is responsible of sensing the radiation and gives a voltage signal which is proportional to it together with the diode leakage. The second (T'_6, D'_1) is shielded from radiation then it gives a voltage signal which is proportional to the leakage current I_L of diode D'_1. The second signal is used to compensate for the leakage of the diode D_1 and therefore to have a signal which is purely proportional to the radiation level (El-Hennawy and Al-Ghamdi 1992, El-Hennawy and Shahab 1990). A difference amplifier (T'_9, T'_{10}, T_9, T_{10} and T_{11}) is implemented to carry out this compensation. This signal is compared, by the

difference amplifier (T_{14}, T_{15}, T'_{14}, T'_{15} and T_{16}) to a reference voltage V_R which is responsible of determining the laser output – power level. The MOSFET string T_{17}, T_{18} and the variable resistance R are designed so as to allow variation of the output power level between two prescribed upper and lower limits. Supplementary MOSFET configurations similar to that used to stabilize the driver are employed here for the same purpose.

2.2 *Theory of Operation*

When the current I of the diode D_1 increases by $\delta I << I$ due to exposure to radiation from the master laser, the source voltage V_5 of the MOSFET T_6 decreases by δV_s so as to accommodate this current variation. Straightforward analysis showed that the corresponding control signal $\delta V_c = \delta V_s - \delta V'_s$ (after amplification and leakage compensation) is given by:

$$\delta V_c = \frac{G_1 k}{1} \delta I$$

where G_1 is the voltage amplification of the amplifier A_1.

If the intensity of radiation (determined by the value of V_R) is so that $\delta V_c = V_R$, the output $\delta V'_c$ from the amplifier A_2 is zero and V_0 and $\delta V'_0$ of the driver remain unchanged ($V_0 = \delta V'_0 = 0$). If δV_c increases (due to an increase of radiation intensity and becomes greater than V_R), then $\delta V'_c$ increases and causes V_0 to decrease and V'_0 to increase. In this case V_{GSN} of T_n and V_{GSP} of T_p are decreased which shifts down the carrier pumping into the floating gate and tends to decrease the radiation intensity and the value of the control signal δV_c. This process continues to decrease δV_c till it becomes equal to V_R. The contrary occurs in the case when the radiation intensity decreases. If V_R is increased (or decreased), $\delta V'_c$ decreases (or increases) and V_0 increases (or decreases) while V'_0 decreases (or increases). Therefore this tends to increase (or decrease) V_{GSN} of T_n and V_{GSP} of T_p which shifts up (or shifts down) the carrier pumping into the floating gate and causes the radiation intensity to increase (or to decrease).

2.3 *Laser Beam Modulation*

The beam modulation is achieved by the V_{mod} voltage which is externally introduced and superimposed on the power-level monitoring signal $\delta V'$ coming from the output of the amplifier T_{14}, T_{15}, T'_{14}, T'_{15} and T_{16} and fed into the amplifier T_1, T_2, T'_1, T'_2 and T_3. The two outputs V_0 and V'_0 of this amplifier which are

complementarily varying are used to control the carrier pumping (electrons and holes) from the channels of MOSFET's T_n and T_p into the floating gate. When V_{mod} increases (decreases), V_0 decreases (increases) and V'_0 increases (decreases) proportionally. This leads to reduce (increase) gate to source votlages of MOSFET's T_n and T_p, therefore, results in a smaller (greater) carrier pumping level and smaller (greater) radiation-power level.

Results and Discussions

This section presents the experimental results that characterise both the MOSFET laser and its on-chip driver. Comparison with the theory is also provided where appropriate along with a general discussion of the findings.

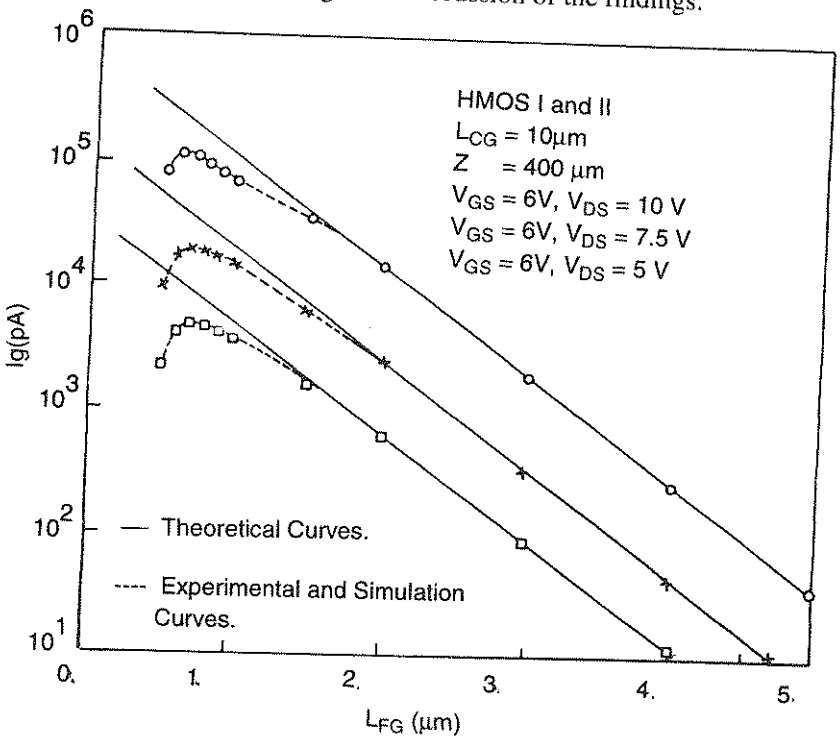

Fig. 5. Variation of I_g at three different values of V_{DS}.

MOSFET Laser Characterization

Figure (5) shows the variation of I_g (which is responsible for the carrier-pumping level) with the MOSFET biasing voltages V_{GS} and V_{DS} (~ 6 to 10 V)

for different values of device geometry (channel length L ~ 5 to 0.5 μm and channel width Z = 400 μm). It can be observed that I_g increases as L is reduced and/or V_{DS} increased. Values of resulting current density J_g as high as 10^3 A/m^2 can be achieved, which are larger than the magnitude of the threshold current required to exite the device lasing (J_{th} ~ 300 to 500 A/m^2). A comparison of these experimental findings with the theoretical predictions shows an excellent match from channel lengths greater than 1.5 μm.

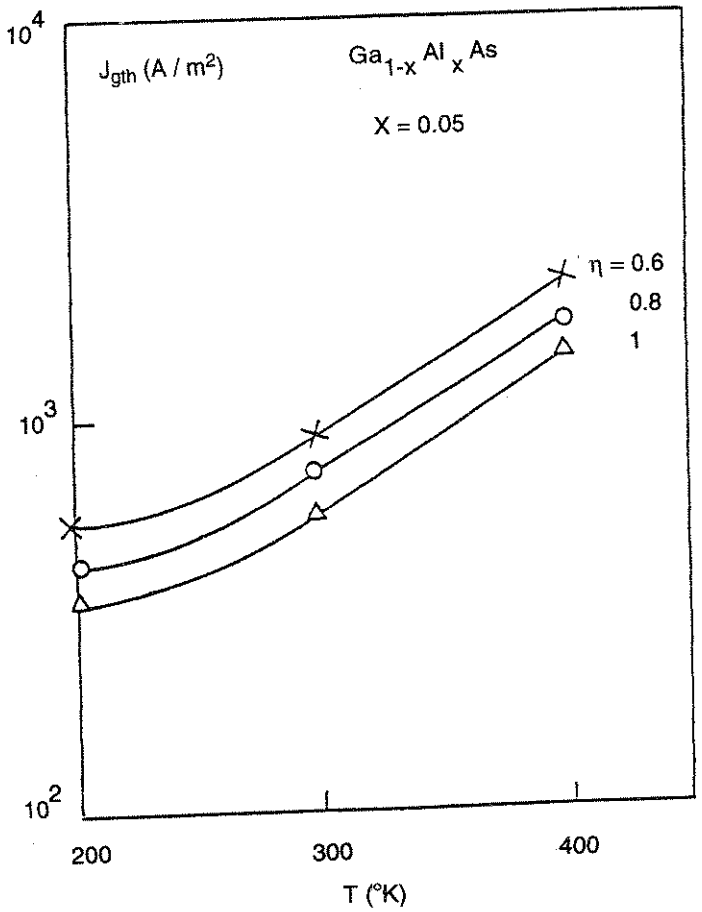

Fig. 6. Variation of J_{gth} with temperature at three different values of quantum efficiency η.

In Figure (6) the variation of threshold current density J_{gth} is depicted against temperature T at different values of quantum efficiency η_i. It is found that J_{gth} increases with increasing T, while a higher value of quantum efficiency results in low threshold current density. It can be inferred from these findings that it is

preferable to operate the laser source at low temeprature in order to keep the active region as cold as possible. As a consequence, power losses caused by crystal and defects scattering would be reduced. These possible improvements were actually observed during the course of this study.

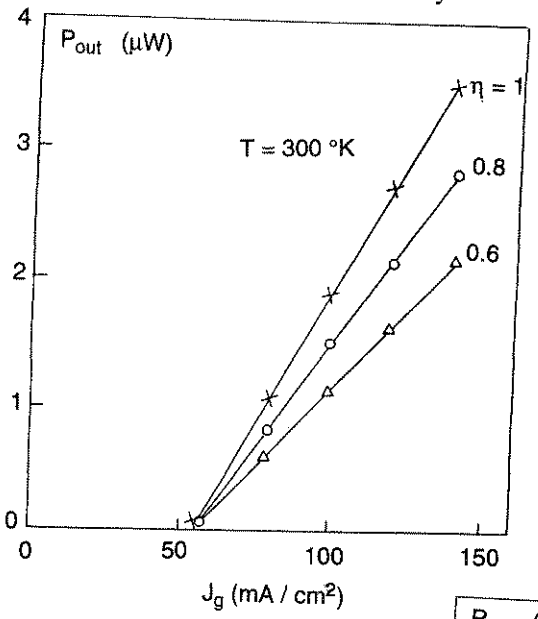

Fig. 7a. Variation of P_{out} with J_g at different values of quantum efficiency η.

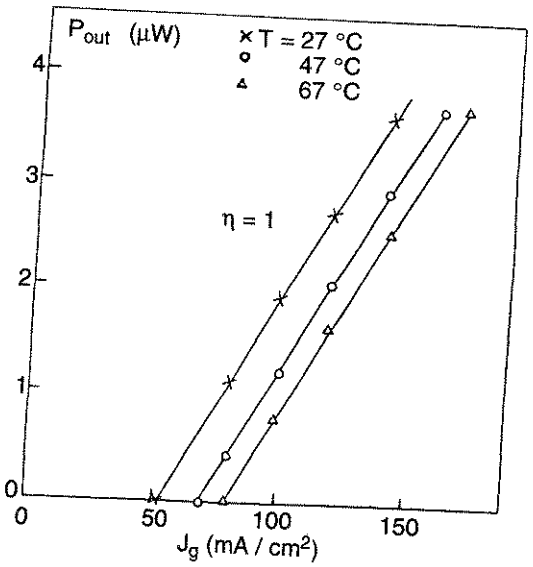

Fig. 7b. Variation of P_{out} with J_g at different values of temperature.

Figures (7a, b) show the variation of P_{out} with the pumping current density J_g for different values of η_i and T. P_{out} increases by increasing J_g and /or decreasing T.

This is because the number of radiative recombination increases with J_g. The output radiations also intensify at high quantum efficiency because the latter translate into low active zone losses. Conversely, the losses increase at high temperatures which are generated either internally through high intensity fields or externally by heating. As a result the efficiency and output power drop.

In the present design, the dual carrier, whereby electrons and holes are simultaneously injected through the oxide layer into the floating gate, results in null current and therefore no power is dissipated in the active zone. This keeps the active zone temperature low and smooth and provides the linearity in the response.

Driver Characterization

Figure (8) shows the variation of driver voltage V_0 and V'_0 with the radiation intensity (indicated as variations in δV_c). Nonlinearity is observed at high radiation intensity. It is associated with amplifier's saturation, and also as the detector becomes no longer linear.

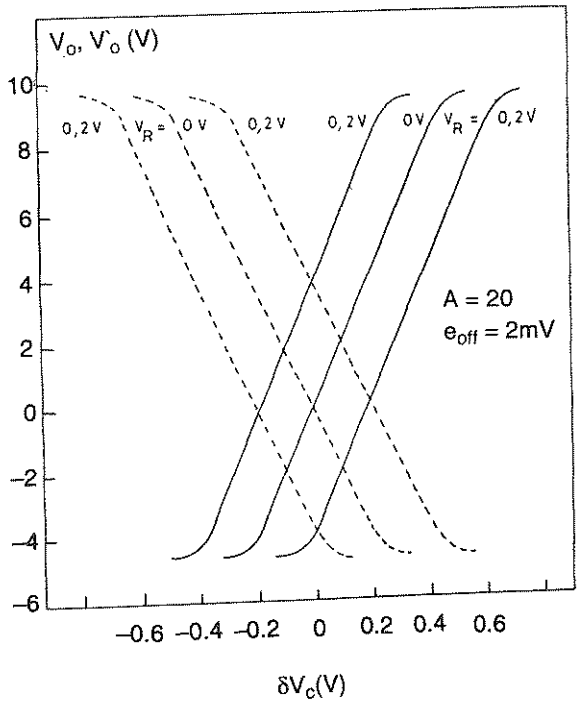

Fig. 8. Variation of V_o, V'_o with radiation inensity δV_c.

Figures (9) and (10) shows the variations of the driver voltage V_0 and V'_0 and the radiation power intensity P_{out} (expressed by $\delta V_c.I_{pA}$) with temperature. Insertion of the feedback loop appreciably decreases the dependence of the radiation and the voltages V_0 and V'_0 on the variations of the ambient temperature T.

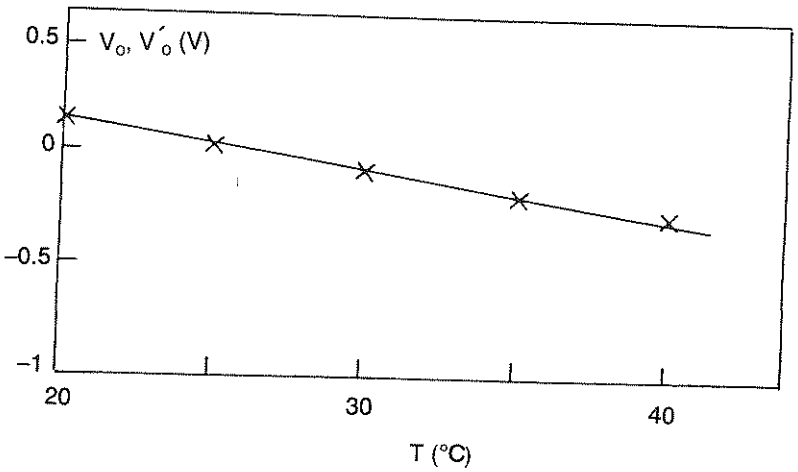

Fig. 9. Variation of V_o, V'_o with temperature.

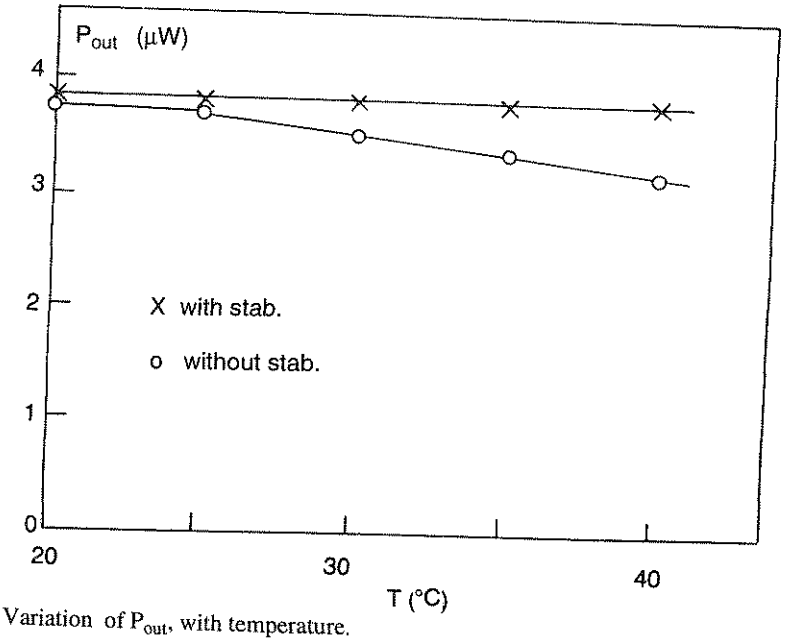

Fig. 10. Variation of P_{out}, with temperature.

Conclusions

A new MOSFET integrated laser source is devised and characterised through intensive experimentation. It has been found to function well under different operating conditions and excellent agreement between the findings and analytical models are achieved. Some of the main advantages include very high power levels at linearity better than 2% and near zero temperature sensivity.

References

El-Hennawy, A., Al-Mrzouki, F. and **Al-Ghamdi, S.** (1993) Study and Characterization of a New Floating Gate MOSFET Laser Source, 18th Int. conf. for SCSSDR Cairo, Egypt, 349-351 pp.

El-Hennawy, A. (1992) Design and Simulation of Non Volatile CMOS EEProm, *Int. J. Elect.* **72:** 37-87.

El-Hennawy, A. and **Al-Ghamdi, S.** (1992) Study and Characterization of MOSFET IC Magnets Detector, *IIE Proc.* **139:** 119-125.

El-Hennawy, A. and **Al-Ghamdi, S.** (1993) Performance Improvement of Lasers by using Trapezoidi - Gate MOSFET's, *IEEE. Proc.* **4:** 69-72.

El-Hennawy, A. and **Mobarek, O.** (1993) Precise Modling of Hot carrier Gate - Current in short - Channel MOSFET's, *IEEE Tran. Elec.* **40:** 19-45.

El-Hennawy, A. and **Shahab, W.** (1990) New Leakage Compensation Technique for Superior CFC, *Int. J. Elec.* **69:** 793-803.

Kressel, H. and **Butler, J.K.** (1977) *Semiconductor Lasers and Hetrojunction LEDS,* Academic Press, Inc., Chapter 12.

Shahab, W. and **El-Hennawy, A.** (1990) New Technique for Offset Compensation and Noise Reduction in MOSFET VLSI., *Int. J. Elec.* **68:** 547-566.

Verdeyen, J.T. (1981) *Laser Electronics,* Prentice Hall Int., Chapter 11.

Wilson, J. and **Hawkes, J.** (1983) Optoelectronic: An Introduction, Prentice Hall Int., 215-216 pp.

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نبائط جديدة من الـ MOSFET : معمولة كمصدر ليزر وغير متأثرة بالحرارة والضوء

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ص .ب (٩٠٢٨) جدة ١١٤١٣ – المملكة العربية السعودية

لقد بذلت جهود عظيمة من بداية التسعينات ولازالت لدراسة أنواع المصادر المستخدمة في الإتصالات بواسطة الالياف البصرية – ونتيجة لهذه الجهود والعمل المتواصل ظهرت نتائج ايجابية ومفيدة سواء في الأبحاث أو التقنيات لهذه المواد .

ومن نتائج هذه الأبحاث الوصول إلى ما يسمى الآن بمصادر الليزر المصنعة من اشباه الموصلات والذي اصبح مصدراً أساسياً لاغنى عنه في الاستخدامات التطبيقية المتنوعة سواء كان ذلك في الاتصالات أو المجالات الأخرى المتعددة .

لقد أثبت هذا النوع من المصادر قدرته على التحكم في كمية الطاقة المستخدمة والمنبعثة منه وتعتمد في تصنيعها على التقنية الحديثة المتقدمة جداً مما أكسبها القدرة على أن تصنع بالأبعاد والأحجام المطلوبة ومثلاً على تلك الأبعاد والتي تتراوح ابعادها ما بين ($\Delta\lambda \sim 0.1$ to 1 Å) وكذلك مصنعه باتجاهات ومقاطع هندسية ($\theta_{\parallel} \sim 5°$ and $\theta_{\perp} \sim 30°$) .

ومما لاشك فيه انه ليس من السهولة التحكم في هذه الأبعاد ولكن للتغلب

على هذه الصعوبات فقد عملت مكونات من الدوائر الكهربائية المساعده والتي تتم بها عملية التحكم في عمل هذه المصادر وسوف يتطرق هذا البحث إلى هذه الدوائر المساعده والتي أثبتت مقدرتها الفائقة على التغلب على هذه العقبات وخاصة التغير الحراري والضوئي والذي يسبب مشاكل كبيرة لمثل هذه المصادر عادة .

وكما هو معروف أهمية المصادر الكهروضوئية في التقدم التقني . وتعتبر الثنائيات الليزرية من أساسيات الخلايا الكهروضوئية المستخدمة في الاتصالات وكذلك في مجالات تطبيقية أخرى متعددة .

ويختص هذا البحث بدراسة شكل جديد من اشكال الليزر يمتاز بأفضليته عن الموجود حالياً لانه خالي من العوائق التصنيعية والتقنية حيث أن هذا المصدر الكهروضوئي يعمل بواسطة المخرج العائم في الـ MOSFET : كذلك يقدم دراسة جديدة لحالات الانبعاث الحراري أو الضوئي ويعطي إمكانية التغيرات المطلوبه عند الاستخدام ويضمن هذا المصدر التحكم في حالة التسرب التياري في الحالات المسموح بها ومن أهمية هذا المصدر الكهروضوئي أيضاً سهولة تركيبه وتشكيله على أي دوائر الكترونية .