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Modelling of Optical Interaction in MOSFET for L Band Application

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Abstract — **Normally off microwave devices like MOSFET are popular due to its high package density, dynamic operating range, low power consumption and sensitivity to light. In this paper, modelling of optical interaction in MOSFET is reported. Sensitivity of S parameters to the light is investigated theoretically at microwave frequency of 1-2GHz i.e. for L band. Noise Figure is lowest in this band when computed in 1 to 10 GHz frequency range. Stability and power gain of the device depends on forward transmission coefficient, S_{21}. Transconductance of the device increases due to optical effect which in turn increases S_{21}. Analysis shows that there is significant optical effect on the stability and various power gains of MOSFET. It is seen that device can be conditionally stable in L band and power gain of the device increases due to optical interaction. Results are computed numerically in MATLAB (7.10 version).**

Keywords – **Microwave, Modelling, MOSFET, Noise Figure, Optical, Stability, Power Gain.**

I. INTRODUCTION

FET devices are sensitive to light. Due to ability of integrating microwave and optical component into a single slice there is a scope for development of microwave optoelectronic system. Optical signal can be converted into electrical signal by means of photodetector, giving the possibility to use optical signal to control microwave devices. This is due to following attractive features [1]:-

1. Neither extra circuit is required to process detected signal nor any parasitic component
2. Isolation from electromagnetic interferences (EMI)
3. Provides an extra Optical control port to the microwave devices
4. They have small dimensions, low losses and short reaction time
5. Possibility of high package density

The integration of microwave optical device as optical microwave monolithic integrated circuit (OMMICS) contributes great impact on the communication industry which demands for highly integrated and reliable systems. Recent advances in high speed modulation of optical carriers have increased focus on transmission of microwave signals. For microwave application MMICs, the GaAs MESFET, HEMT and HBT are primary active devices. Although exhibiting remarkable microwave gain, these devices suffers from limited range in logic operation. The normally off microwave devices like N-channel enhancement mode MOSFET having dynamic operating range are the devices of interest.

This paper investigates optical effect in microwave device theoretically. Stability of MOSFET based on S-parameters is investigated for L band i.e. 1-2 GHz as noise figure of MOSFET is lowest in this band[11]. Section 2 explains theory of stability and its testing criterion. In section 3 modelling details of optical interaction in the device is given. Results of modelling and simulation are discussed with section 4. It also gives validation of results with results of ADS tool. Conclusion of the investigation is given in section 5.

II. STABILITY OF THE DEVICE

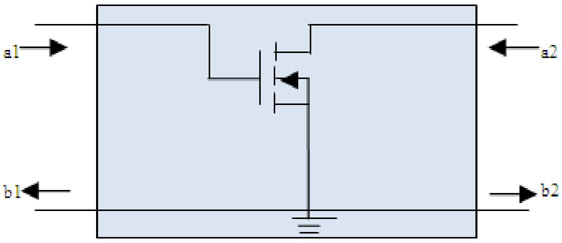

Figure 1 MOSFET as Two Port Network

Figure 1 shows metal oxide semiconductor field effect transistor (MOSFET) as two port network in common source configuration where a1, a2 are incident waves and b1, b2 are reflected waves. S parameters of the device are computed for the reason that S parameters with CAD tools can be used in analog and RF circuit simulation process [8].

The design of a microwave transistor based circuit requires testing of the device performance based on the S parameters. The most important design considerations are stability, power gain, bandwidth, noise and DC requirements. Present work deals with testing of stability of the device based on K-delta and μ test which are discussed in subsequent topics. Optical effect on stability and various power gains of the device is reported.

Let us explore the necessary and sufficient conditions for a transistor amplifier to be stable at microwave range. In the microwave circuit oscillation is possible if either the input or output port impedance has a negative real part; this would then imply that $|S_{11}| > 1$ or $|S_{22}| > 1$.
There are two types of stability criterion [2, 3]:

Unconditional Stability: The network is unconditionally stable if $|S_{11}| < 1$, $|S_{22}| < 1$ and $K>1$ for all passives source and load impedances

Conditional Stability: The network is conditionally stable if $K<1$. This case is also referred as potentially unstable.

It is possible for an amplifier to be stable at its design frequency, but unstable at other frequencies. Proper care should be taken while designing the amplifier.

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To determine the stability of the device following tests are used :

1. K - Δ test or Rollet's condition
2. μ Test

1. *K - Δ Test:*

The first step in designing the amplifier with the S parameter method is to determine whether the transistor is unconditionally stable or potentially unstable. This can be easily estimated using the K stability factor and delta. With K - Δ test, a device will be unconditionally stable if Rollet's condition, defined as K > 1 is satisfied. K is called as Rollet's stability factor and is given by - $K = \left\{\frac{\left(1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2\right)}{2.|S_{11}||S_{22}|}\right\}$ --- (2. 1)

and the auxiliary condition that $|\Delta| < 1$ is simultaneously satisfied. where,

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| \quad \text{---- (2.2)}$$

these two conditions are necessary and sufficient for unconditional stability of the device. If the device S parameters do not satisfy the K - Δ test, that is, if the stability factor is less than unity, device is said to be conditionally stable or potentially unstable. There are certain limitations for the K - Δ test since it involves constraints on two separate parameters.

2. *μ Test:*

Another criterion for testing the stability of the amplifier involves a single parameter μ defined as μ > 1. Here μ is given, as -

$$\mu = \left\{\left(1 - |S_{11}|^2\right)/\left(|S_{22} - \Delta.S'_{11}| + |S_{12}.S_{21}|\right)\right\} \text{-(2.3)}$$

Where ' indicates transpose of S_{11}. Thus, if μ > 1, the device is unconditionally stable. Larger values of μ imply greater stability. A device is said to be potential unstable if μ < 1.

III. MODELLING OF OPTICAL EFFECT

To investigate the optical interaction in MOSFET, characterization of S parameters of the device in common source configuration is carried out. Device under consideration with port termination of 50 ohm is as shown in figure 2.

The normally off microwave device like n- channel MOSFET when illuminated, due to optical absorption, photo generation of carriers takes place within the device.

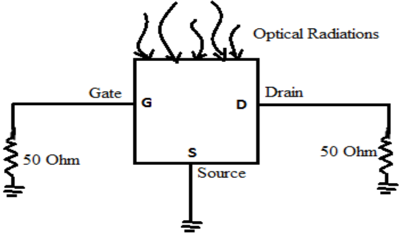

Fig.2. Prospective View of the Device under consideration

When the illumination has photon energy equal to or greater than band gap energy of the semiconductor, the photo extension of free carriers (e-h pairs) takes place. The photon energy is related to wave length λ of incident light and is given by Eph= h*c/λ, where h is Plank's constant and c is speed of light.

Silicon has 1.1 eV of band gap energy. The free carriers will be generated only if the wave length of incident light is less than or equal to 870 nm which can be obtained from slandered laser diode. For current investigation optical radiations are made to incident perpendicular to the surface and wave length of radiation is taken as 800 nm with optical power of 0.25mW. Photogenerated carriers are induced due to optical absorption and gives rise to photovoltage which in turn reduces the width of depletion region as shown in figure 3. Modelling of this process is given as below [4, 5]. Operating principle of MOSFET in microwave range is characterized by minority-carrier transport [6]. The transport mechanism in the inversion region constitutes drift and recombination. The continuity equation for the carriers is given by a first order differential equation. For holes it is written as follows -

$$\frac{\partial p(y,t)}{\partial t} = \frac{1}{q}\frac{\partial Jp(y,t)}{\partial y} + G - \frac{p(y,t)}{Tp} - \frac{R_S\tau_p}{S_p} \quad \text{---- (3.1)}$$

Equation (3.1) is solved under ac condition resulting a solution for hole density and is given by equation 3.2

$$P(y) = \frac{\alpha\varphi_1\tau_{\omega p}}{(1-\alpha v_y\tau_{\omega p})}e^{-\alpha y} - \frac{N_\tau K_p\tau_p\tau_{\omega p}\varphi_1\alpha}{S_p} + Cexp\left(\frac{y}{v_y\tau_{\omega p}}\right) \text{-- (3.2)}$$

where Sp : surface recombination velocities for holes and the term R_s is given as,

$$R_s = N_\tau K_p\tau_p\varphi_0\alpha + N_\tau K_p\tau_p\varphi_1\alpha \quad \text{--- (3.3)}$$

$\tau_{\omega p}$ Lifetime of holes under ac condition;

The constant C of (3.2) is evaluated using the boundary condition at $y = Y_{Dg}$, and hence equation 3.2 becomes, $= \alpha\varphi_1\tau_{\omega p}e^{-\alpha y_{dg}}$; here y_{dg} is the width of the gate depletion measured from the surface. The sidewalls of the gate depletion region are assumed quarter arcs. Considering the arcs at the source and drain ends to have radii r_1 and r_2, respectively, where $r_1 = y_{Ds}$ at source side and $r_2 = y_{Dd}$ at drain side. The number of holes crossing the junction at $y = 0$ is given by $P(0) = \frac{\pi}{4}Z(p_1{r_1}^2 + p_2{r_2}^2)$ ---- (3.4)

$$P_1 = \alpha\varphi_1\tau_{\omega p}e^{-\alpha r_1}\ ;\ P_2 = \alpha\varphi_1\tau_{\omega p}e^{-\alpha r_2} \quad \text{---- (3.5)}$$

Where α is absorption coefficient, $\tau_{\omega p}$ is mean life time of minority carriers and is frequency (ω) dependent factor, ϕ1 is flux density of incident radiations. The photovoltage generated in depletion layer which is function of α, ω and ϕ, can be calculated by using equation 3.6 [5]

$$V_{op} = \varphi_b\, ln\left[\frac{qv_y\frac{\pi}{4}Z\left(P_1{Y_{Ds}}^2+P_2{Y_{Dd}}^2\right)}{J_{s1}}\right] \quad \text{----- (3.6)}$$

where, Js1 is the reverse saturation current density. This generated photovoltage modifies the depletion width and hence the surface potential.

Depletion layer width at source side can be calculated from equation 3.7

$$Y_{Ds} = \sqrt{\frac{2\epsilon}{qN_a}\left(\phi_B - \delta + v_s - v_{gs}\right)} \quad \text{---- (3.7)}$$

and depletion width at drain side is given as

$$Y_{Dd} = \sqrt{\frac{2\epsilon}{qN_a}\left(\phi_B - \delta + v_D - v_{gs}\right)} \quad \text{----- (3.8)}$$

Width of gate induced depletion region can be given as, $Y_{Dg} = Y_{Dd} - Y_{Ds}$ ----- (3.9)

Under illumination, due to generated optical voltage depletion widths at source, drain and gate Y_{Ds}, Y_{Dd}, Y_{Dg} respectively gets modified to $Y_{Ds}', Y_{Dd}', Y_{Dg}'$ and computed with equation 3.10, 3.11 and 3.12

$$Y_{Ds}{}' = \sqrt{\frac{2\epsilon}{qN_a}\left(\phi_B - \delta + v_s - v_{gs} - v_{op}\right)} \quad \text{----- (3.10)}$$

$$Y_{Dd}{}' = \sqrt{\frac{2\epsilon}{qN_a}\left(\phi_B - \delta + v_d - v_{gs} - v_{op}\right)} \quad \text{----- (3.11)}$$

$$Y_{Dg}{}' = Y_{Dd}{}' - Y_{Ds}{}'$$

In 3.7 - 3.11, v_s is the source voltage and v_d is drain voltage, v_{gs} is gate to source voltage, v_{op} is photo voltage, ϕ_B is the bulk potential, δ is the position of Fermi level at the neutral region below the conduction band. Figure 3 shows prospective view of depletion width modulation.

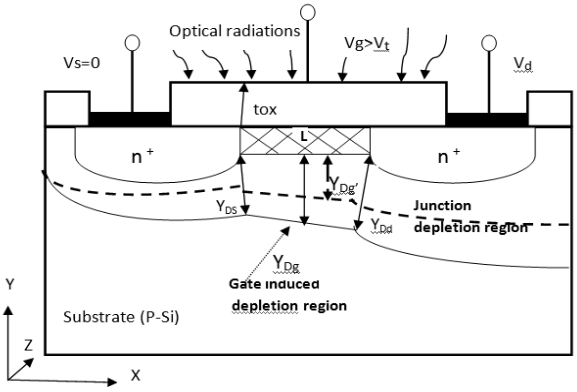

Fig.3. Prospective View of MOSFET giving Effect of Illumination on Depletion Width

Dashed line shows decreased depletion width due to application of photovoltage. The reduction in depletion width due to optical interaction causes increase in drain current. This increase in drain current increases the transconductance of the device.

There are number of applications which require microwave measurements in L band [9, 10]. S parameters are computed in this band by conversion of optically controlled Y parameters [7] to S parameters, as given below

$$S_{11} = \frac{\left((Y_{0op}-Y_{11op})+(Y_{0op}+Y_{22op})+(Y_{12op}.Y_{21op})\right)}{\Delta Y} \quad \text{----- (3.12)}$$

$$S_{12} = -\frac{2.Y_{12op}}{\Delta Y} \quad \text{----- (3.13)}$$

$$S_{21} = -\frac{2.Y_{21op}}{\Delta Y} \quad \text{----- (3.14)}$$

$$S_{22} = \frac{\left((Y_{0op}+Y_{11op}).(Y_{0op}-Y_{22op})+(Y_{12op}.Y_{21op})\right)}{\Delta Y} \quad \text{----- (3.15)}$$

Device is assumed to be unilateral. For perfect match, Transducer Power Gain or insertion gain of transister is given as, $G_T = S_{21}{}^2$ ---- (3.16)

It is also called as Forward power gain of the device as it is a function of forward transmission coefficient S_{21}.

Various Power Gains are as given below-

Maximum stability gain $G_{msg} = \frac{S_{21}}{S_{12}}$ ---- (3.17)

Maximum Transducer Power Gain-

$G_{max} = G_{msg}.\left(k - \sqrt{k^2 - 1}\right)$ ---- (3.18)

Maximum unilateral transducer power gain-

$GU_{max} = \frac{S_{21}{}^2}{\left((1-S_{21}{}^2)(1-S_{12}{}^2)\right)}$ ----- (3.19)

Available Power Gain or gain associated with output matching network, $G_A = \frac{S_{21}{}^2}{(1-S_{22}{}^2)}$ ---- (3.20)

Operating Power Gain or gain associated with input matching network $G_P = \frac{S_{21}{}^2}{(1-S_{11}{}^2)}$ ---- (3.21)

IV. RESULTS AND DISCUSSIONS

Optical voltage is computed with equation 3.6 and is plotted against incident radiations having flux density in Wb/m^3. Figure 4 shows that induced optical voltage increases logarithmically with incident radiations. Increase in optical voltage increases drain current and transconductance of MOSFET under illumination[12]. Figure 5 shows optical control of transconductance for varying optical power of 0.25mW, 2.5mW and 25mW.

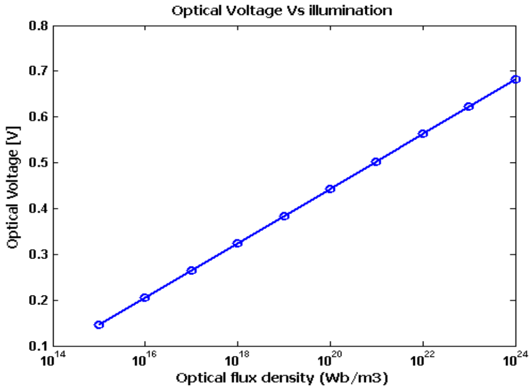

Fig.4. Optical Voltage versus Illumination in Wb/m3

Figure 6 and 7 shows optical effect on magnitude of S_{11} and S_{22} respectively. It shows that magnitude of S_{11} and S_{22} decreases i.e. reverse losses decrease under illumination.

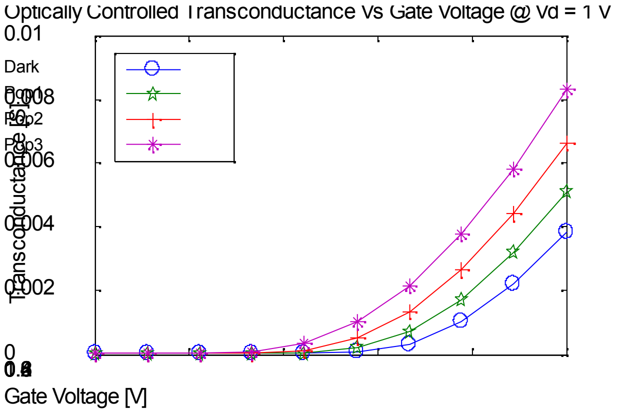

Fig.5. Optically Controlled Transconductance Vs Gate Bias

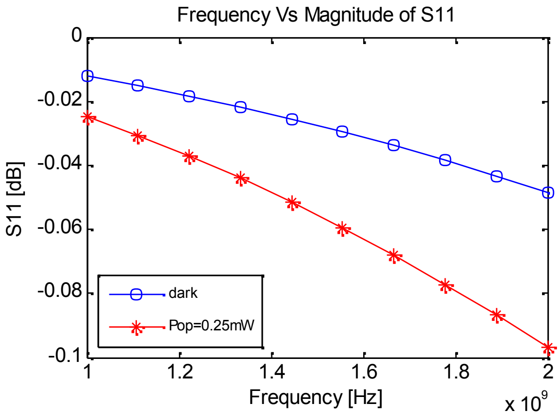

Fig.6. Optical Effect on magnitude of S11

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Under dark and illuminated condition, $S_{11}$and S_{22} is less than one which satisfies the necessary condition of stability.

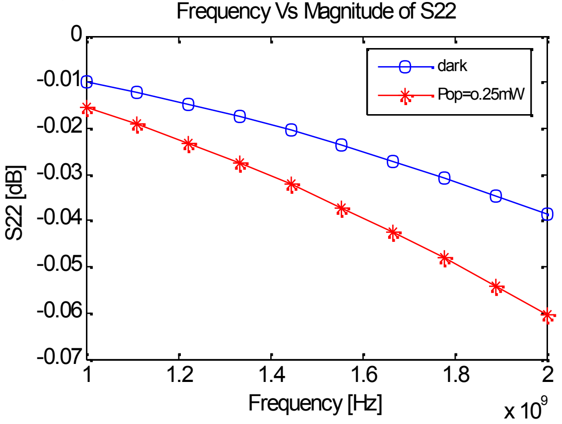

Fig.7. Optical Effect on magnitude of S22

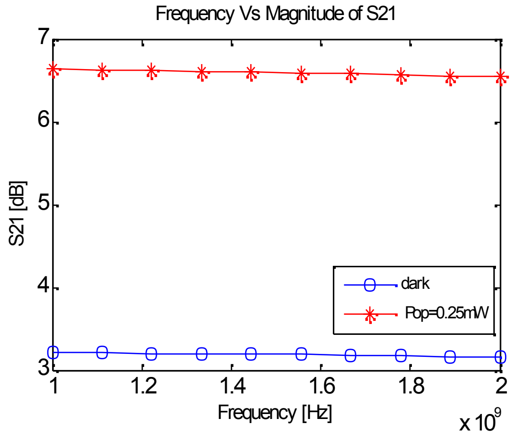

Fig.8. Optical Effect on magnitude of S21

Figure 8 shows optical effect on S_{21} which is the function of transconductance of the device. Under illumination transconductance of the device increases [12], this increases magnitude of S_{21}. Forward transmission increases due to increase in S_{21}.

There is no significant effect of light illumination on S_{12} as shown in figure 8

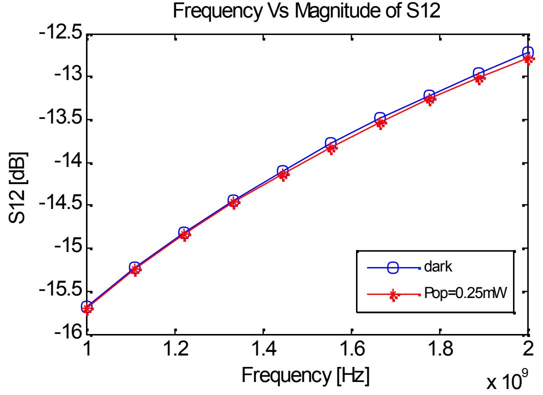

Fig.9. Optical Effect on magnitude of S12

Stability factor K is computed by equation 2.1. From Figure 9, value of K is less than one, indicates conditional stability of the device in dark and under illumination.

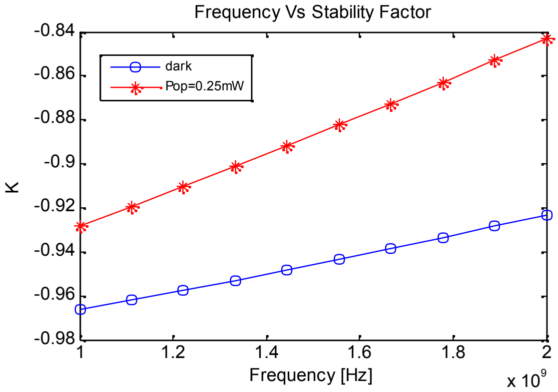

Fig.10. Optical Effect on Stability factor

Increase in S_{21} and decrease in S_{11} and S_{22} under illumination,, magnitude of Δ increases which in turn increases the stability factor K as shown in figure 10 and 11 respectively. It shows magnitude of K and Δ is less than one. For stability of the device factor delta should be less than unity and K should be greater than unity.

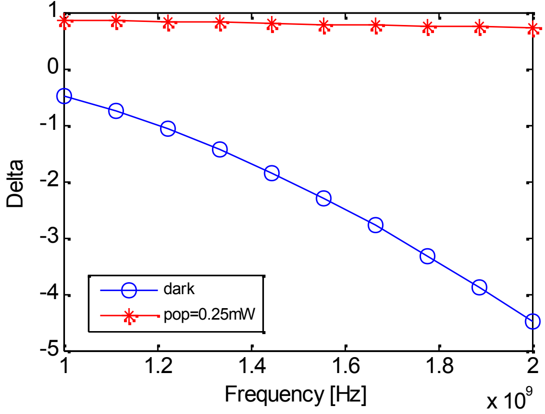

Fig.11. Optical Effect on Delta Factor

Result of μ test is shown in figure 10 which is graphical interpretation of equation 2.3. Under dark and illumination, μ<1 i.e. device is potentially unstable. Greater is the value of μ more is the stability of the device.

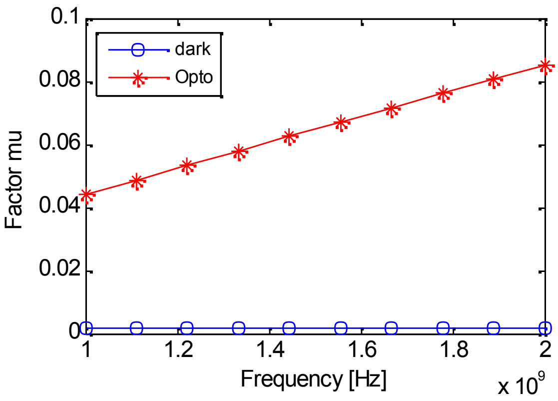

Figure 11: Optical Effect on μ factor

In all above results -o- indicates parameter value in dark condition -*- indicates optical or photo effect on that parameter value.

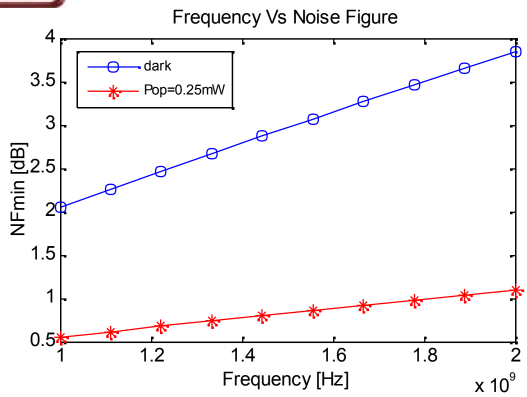

Fig.12. Optical Effect on Noise Figure

In [11] Noise figure of Optically Gated MOSFET is reported. It is seen that in L band Noise Figure is lowest. Noise behaviour of device in L band is as shown in figure 12.

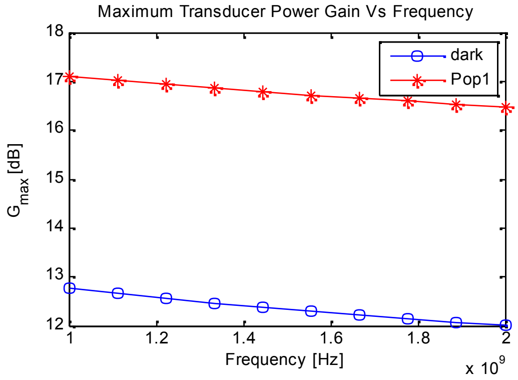

Fig.13. Maximum Transducer Power Gain under dark and Illumination

Maximum transducer power gain and maximum unilateral transducer power gain is computed by equation 3.18, 3.19 whose result is shown in figure 13, 14 respectively.

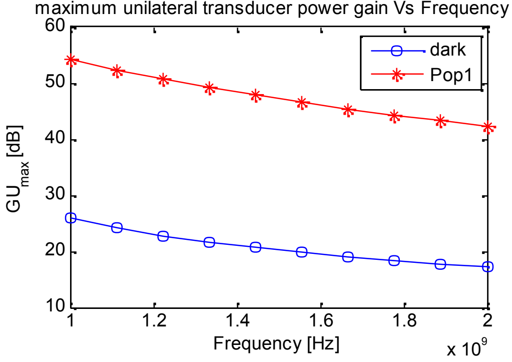

Fig.14. Maximum Unilateral Transducer Power Gain under dark and Illumination

Figure 15 shows optical effect on transducer power gain of the device computed with equation 3.16. It increases under illumination and can be controlled optically by varying optical power from 0.25mW to 25 mW. Optical power is the third controlling port of a device. In same manner operating power gain, available power gain and maximum stability gain of the two port network can be controlled as shown in figure 16, 17 and 18 respectively.

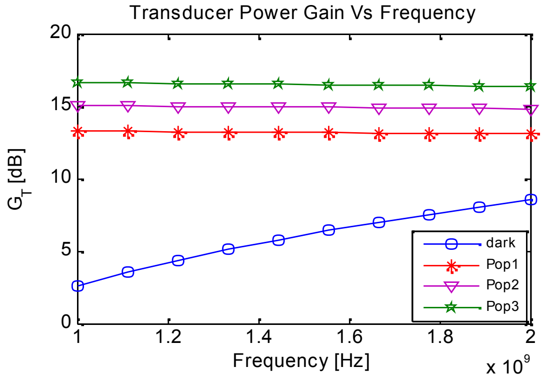

Fig.15. Optical Control of Transducer Power gain

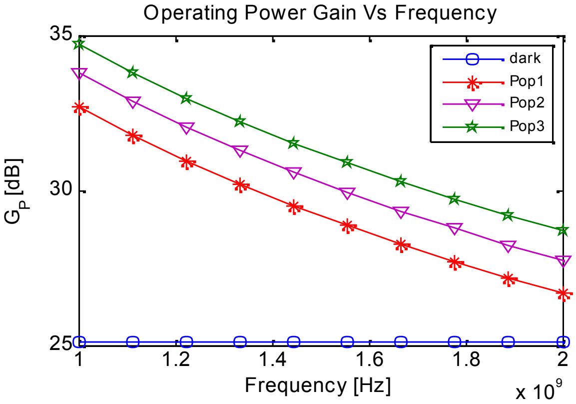

Fig.16. Optical Control of Operating Power Gain

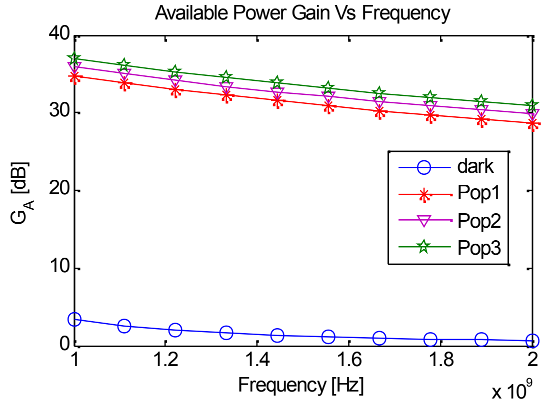

Fig.17. Optical Control of Available Power Gain

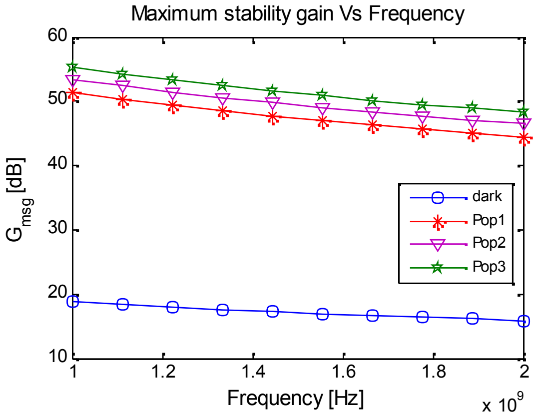

Fig.18. Optical Control of Stability Gain

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V. CONCLUSIONS

MOSFET is considered as two port network. Investigation is carried out for L band as Noise Figure is lowest in this frequency band. Sensitivity of scattering parameters to light is reported in this paper. Due to optical effect, parameter values of S_{11} and S_{22} decreases hence reducing the return losses. Magnitude of forward transmission coefficient S_{21} increases due to increase in transconductance of the device. Power gains of the device are in the form of S_{21} which shows significant rise due to optical interaction in L band. Two port parameters can be controlled with additional optically controlled port. Stability of the device is tested by K-Δ and μ test. As Rollet's stability factor, K is less than unity; device can be conditionally stable in L band. Noise Figure of two port network decreases significantly under illumination. This performance of device is suitable for L band applications like low noise amplifier with suitable matching network in radar or for GPS applications. Application may be extended as an oscillator, as the device may get oscillate due to unstable performance in this band.

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