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Speed of Operation Estimation and Transmission Performance Efficiency of Different Optical Laser Sources under Thermal Effects and Different Doping levels

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Abstract— **This paper has presented the mathematical model formulation of transmission performance evaluation of different optical sources under the thermal and spectral effects with different dopant levels over wide range of the affecting parameters. We have taken into account the rise time effects on the transmission bit rates within using non return to zero coding (NRZ). The cut-off wavelength, threshold current, the threshold optical gain, total quantum efficiency, reflection loss, modulation index, gain bandwidth product, spectral line width of different optical sources compounds are deeply investigated in relation to different dopant levels and thermal effects.**

Keywords— **Total quantum efficiency, Cut-off wavelength, Dopant levels, Threshold current, and Reflection loss.**

I. Introduction

For many applications requiring a two-dimensional laser array or monolithic integration of lasers with electronic components (e.g., optical interconnects), it is desirable to have the laser output normal to the surface of the wafer. Such lasers are known as surface-emitting lasers. Two categories of laser exist where light is emitted normal to the surface of the wafers. The first category consists of lasers where the active region has the conventional waveguide form, but the light is deflected normal to the surface using mirror or a diffraction grating fabricated adjacent to the laser waveguide. Lasers of this type have been fabricated using both the GaAs-AlGaAs ($\lambda \sim 0.85$ μm) and the InGaAs-GaAs ($\lambda \sim 0.9$-1.05 μm) material systems. In the second category the surface-emitting lasers have their optical cavity normal to the surface of the wafer. These devices are known as vertical-cavity surface-emitting lasers (VCSELs) [1-3]. A number of advantages, including large aperture, single-longitudinal-mode operation, and ease of integrability, make them ideal for many high-speed optoelectronic integrated circuit applications and optical computing. VCSELs have recently been shown to generate picosecond and femtosecond high power pulses under optical pumping from another laser. By decreasing the pulse width of pumping optical pulses to 200 fs, a VCSEL laser pulse width of under 190 fs has been measured. Optical pumping of semiconductor lasers is obviously unsuitable for most application. Gain switching of VCSELs using electrical excitation has been demonstrated to yield pulses of 17 to 30 ps at repetition rates up to 8 GHz. The high-speed and modulation properties of VCSELs are in the early stages of investigation. However , the experimental and theoretical results that have been obtained are very promising. The maximum observed relaxation oscillation frequency was measured to be around 71 GHz. This implies that VCSELs have potentially very high modulation bandwidths [2, 3]. Laser diodes have grown to a key component in modern photonics technology. Optically pumped semiconductor lasers offer significant advantages with respect to all traditional diode pumped solid state lasers (including fiber lasers) in regards to wavelength flexibility, broad pump tolerance, efficient spectral and spatial brightness conversion and high power scaling.

Semiconductors are in many ways ideal laser materials. They are suitable for both optical pumping and direct electrical pumping, they are able to produce high optical gain and their quantum efficiency is high. Their emission is not limited to discrete lines set by atomic levels but can instead be chosen by design. Similarly multi-layered structures with varying index of refraction can be fabricated with great precision [4]. The same physical processes that are responsible for such advantages impose limitations on the kind of devices that can be realized. In order to achieve optical gain in semiconductor, the active material cannot have arbitrary shape: one of the dimensions must be small (a few microns in the case of optical pumping, around one micron or less for electrical pumping), thus defining a plane that dictates the geometry of the laser devices [2]. To date, the typical (and enormously successful) implementation of the semiconductor laser is what is commonly known as a "laser diode", variations of which can be found everywhere. Laser diodes are electrically pumped monolithic devices, contained within a "chip" of semiconductor material with typical dimensions around one millimeter. In spite of its many applications, this particular implementation of the semiconductor laser severely limits the performance of semiconductors as laser materials [5]. If laser emission is in a direction contained in the plane, the most common case known as "edge emitters", the laser is optically just a waveguide with gain, the modal characteristics of the laser defined by the waveguide. In order to obtain single mode operation the mode size has to be small (typically 1×3 μm) and the output power is limited by optical damage at the facets. High power can be obtained of course, but at the expense of brightness. Optical pumping of semiconductors had long been used as one of the early steps in the development of new semiconductor lasers, but usually as a research tool, not with the objective of creating a practical device but as a means of learning about material properties, i.e. as a step towards the ultimate goal of creating a monolithic, electrically driven device, a laser diode. Only recently there has been increased academic interest on the technology as a means to producing unique practical devices, a review of the theory of operation and recent activity [6, 7].

The paper is organized in the following sections. Section II has explained the mathematical model equations in more details. Section III has presented the simulation results and performance evaluation of different optical sources under different dopant levels and ambient temperatures. Finally, section IV has presented the conclusion part.

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II. MODEL ANALYSIS

The band gap energy for trivalent optical source compounds in terms of aluminum, gallium, phosphide and arsenide dopants can be given the following mathematical relations [8-12]:

$E_g(eV)=1.351+2.23\,x$ for $Al_xIn_{1-x}P$ (1)

$E_g(eV)=1.442+1.266\,x+0.266\,x^2$ for $Al_xGa_{1-x}As$ (2)

$E_g(eV)=0.726+1.129\,x+0.368\,x^2$ for $Al_xGa_{1-x}Sb$ (3)

$E_g\,(eV)=1.424+1.15\,y+0.176\,y^2$ for GaP_yAs_{1y} (4)

$E_g\,(eV)=0.368+0.891\,y+0.101\,y^2$ for InP_yAs_{1-y} (5)

Where x is the aluminum dopant, and y is the phosphide dopant. The cut-off wavelength and reflection loss of the optical laser diode sources can be given by [12, 13]:

$$\lambda_c = \frac{1.24}{E_g\,(eV)} \quad (6)$$

$$R = \left(\frac{n-1}{n+1}\right)^2 \quad (7)$$

Where n is the refractive index which Ref. [14] has proposed an empirical relation between the refractive index and the band gap energy for a variety of optical source compounds as the following relation:

$$n = \sqrt{\frac{12.417}{E_g(eV)-0.365}} \quad (8)$$

The threshold current of optical laser diode source can be described the following formula [12, 15]:

$$I_{th}=J_{th}\,L\,W \quad (9)$$

Where L is the optical cavity length, W is the cavity width, and J_{th} is the threshold current density which is given by:

$$J_{th} = \frac{1}{\beta}\left[\alpha + \frac{1}{2L}\ln\left(R^{-2}\right)\right] \quad (10)$$

Where β is the gain factor, and α is the loss coefficient. The optical gain at lasing threshold can be given by [12, 16]:

$$g_{th}\,(dB/cm) = 10\log\,(\alpha + \frac{1}{2L}\ln(R^{-2})) \quad (11)$$

As well as the spectral line width of optical laser diode source can be described by the following formula [12, 17]:

$$\Delta\lambda = \frac{\lambda^2}{2\,n\,L} \quad (12)$$

Finally, the total quantum efficiency of optical laser diode source is given by [12, 18, 19]:

$$\eta_T = \frac{q\,P}{I_P\,E_g} \quad (13)$$

The optical laser diode source device rise time can be given by the following relation:

$$t_r = 2.2\left[\frac{2\,k\,T\,C_S}{q\,I_P} + \tau\right] \quad (14)$$

Where C_S is the space charge capacitance, I_P is the photocurrent, k is the Boltzmann's constant ($1.38\text{x}10^{-23}$ J/K), q is the electron charge ($1.6\text{x}10^{-19}$ C), and T is the ambient temperature. By substituting the photo current from Eq. 13 into Eq. 14, the deduced can be described by the following formula:

$$t_r = 2.2\left[\frac{\dfrac{2\,k\,T\,C_S}{q^2\,P}}{\eta_T\,E_g} + \tau\right] \quad (15)$$

As well as the threshold gain bandwidth product or device figure of merit (FOM) can be given by [12]:

$$FOM = g_{th}\,BW \quad (16)$$

Where BW is the device bandwidth with non return to zero coding ($BW=0.7/t_r$), and g_{th} is the threshold optical gain.

III. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

The model has been investigated the performance parameters of different optical sources compounds with different dopant levels and thermal effects environments over wide range of the affecting parameters as listed in Table 1.

Table 1. List of the parameters used in the simulation [3, 5, 12, 14, 16].

Operating parameter	Value and unit
Ambient temperature, T	300 K ≤ T ≤ 400 K
Optical signal wavelength, λ	1.55 μm
Aluminum dopant, x	0.0 ≤ x ≤ 0.5
Phosphide dopant, y	0.0 ≤ y ≤ 0.5
Space charge capacitance, C_S	500 μF
Photocurrent, I_P	50 mA
Carrier life time, τ	5 nsec
Optical cavity length, L	250 μm
Cavity width, W	20 μm
Gain factor, β	$2\text{x}10^{-4}$ A/cm^3
Loss coefficient, α	10 cm^{-1}
Optical incident power, P	100 mW

Based on the clarified figures from Figs. (1-22), and based on the basic mathematical relations model with the assistant of operating parameters, the following facts are assured:

i) Fig 1 has assured that $Al_xGa_{1-x}As$ has presented the lowest cut-off wavelength and reflection loss in comparison with other different optical sources compounds without any dopant added and under the same operating conditions. While InP_yAs_{1-y} has presented the highest cut-off wavelength and reflection loss in comparison with other different optical sources compounds without any dopant added and under the same operating conditions.

ii) Fig. 2 has demonstrated that $Al_xGa_{1-x}As$ has presented the lowest threshold current and the highest threshold optical gain in comparison with other different optical sources compounds without any dopant added and under the same operating conditions. But InP_yAs_{1-y} has presented the highest threshold current and the lowest threshold optical gain in comparison with other different optical sources compounds without any dopant added and under the same operating conditions.

iii) Fig. 3 has indicated that $Al_xGa_{1-x}As$ has presented the highest spectral linewidth and the lowest total quantum efficiency in comparison with other

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different optical sources compounds without any dopant added and under the same operating conditions. While InP_yAs_{1-y} has presented the lowest spectral linewidth and the highest total quantum efficiency in comparison with other different optical sources compounds without any dopant added and under the same operating conditions.

iv) Figs. (4-6) have indicated that $Al_xGa_{1-x}As$ has presented the lowest rise time and the highest figures of merit in comparison with other different optical sources compounds without any dopant added and under the same operating conditions. While InP_yAs_{1-y} has presented the highest rise time and the lowest figure of merit in comparison with other different optical sources compounds without any dopant added and under the same operating conditions. These figures have presented the dramatic thermal effects on the increased rise time and the decreased optical source figure of merit.

v) Figs. (7, 8) have proved that both cut-off wavelength and reflection loss decreases with increasing aluminum dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

vi) Figs. (9, 10) have indicated that threshold current decreases and optical threshold gain increases with increasing aluminum dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

vii) Figs. (11, 12) have assured that spectral linewidth slightly increases and total quantum efficiency slightly decrease with increasing aluminum dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

viii) As shown in Figs. (13, 14) have indicated that rise time decreases and optical laser diode sources figure of merit increases with increasing aluminum dopant ratio for different optical laser diode sources compounds and under the same operating considerations and room temperature effects.

ix) Figs. (15, 16) have proved that both cut-off wavelength and reflection loss decreases with increasing phosphide dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

x) Figs. (17, 18) have indicated that threshold current decreases and optical threshold gain increases with increasing phosphide dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

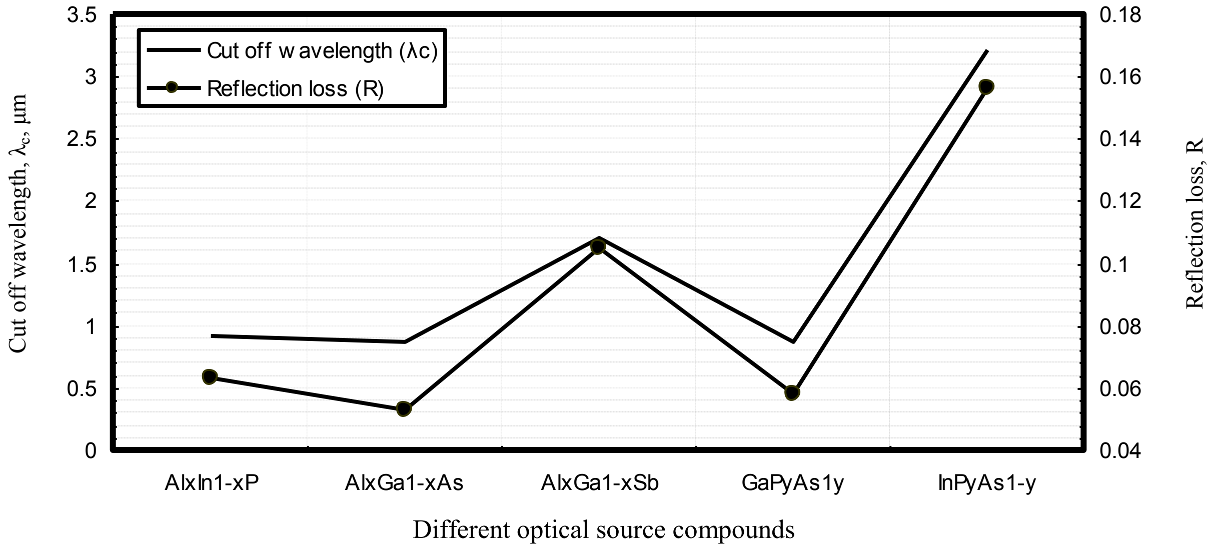

Fig. 1. Cut off wavelength and reflection loss versus different optical sources compounds without any dopant ratio added at the assumed set of the operating parameters.

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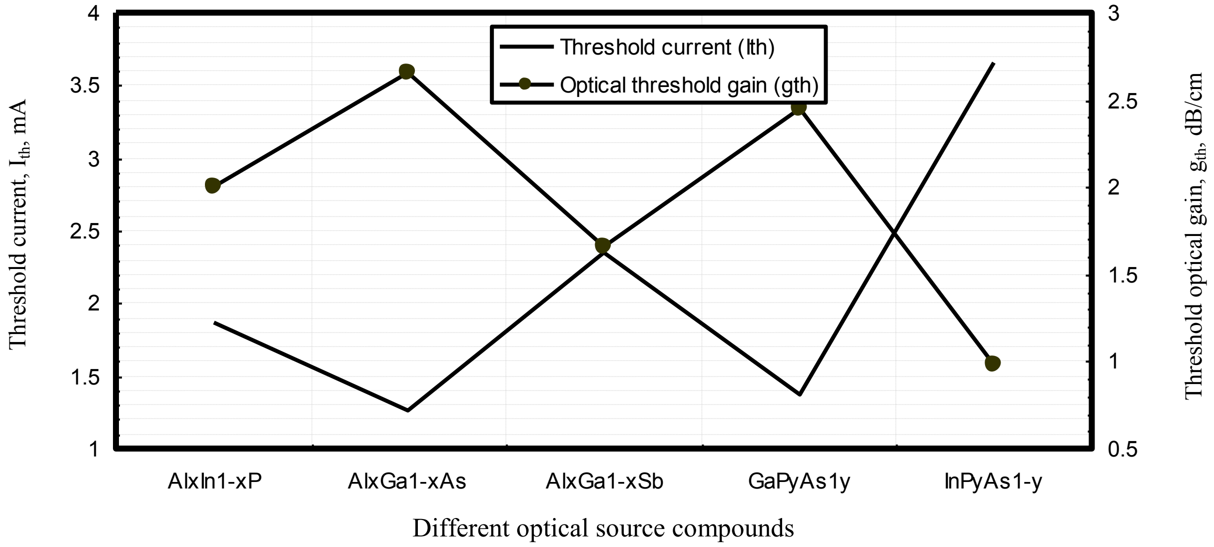

Fig. 2. Threshold current and optical threshold gain against different optical sources compounds without any dopant ratio added at the assumed set of the operating parameters.

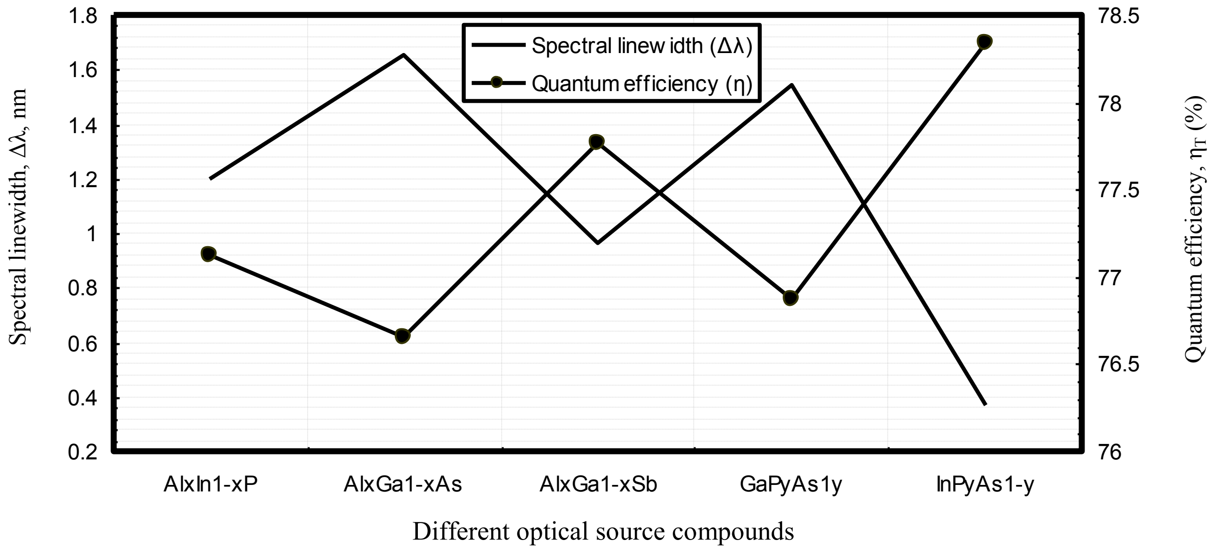

Fig. 3. Spectral line width and total quantum efficiency and against different optical sources compounds without any dopant ratio added at the assumed set of the operating parameters.

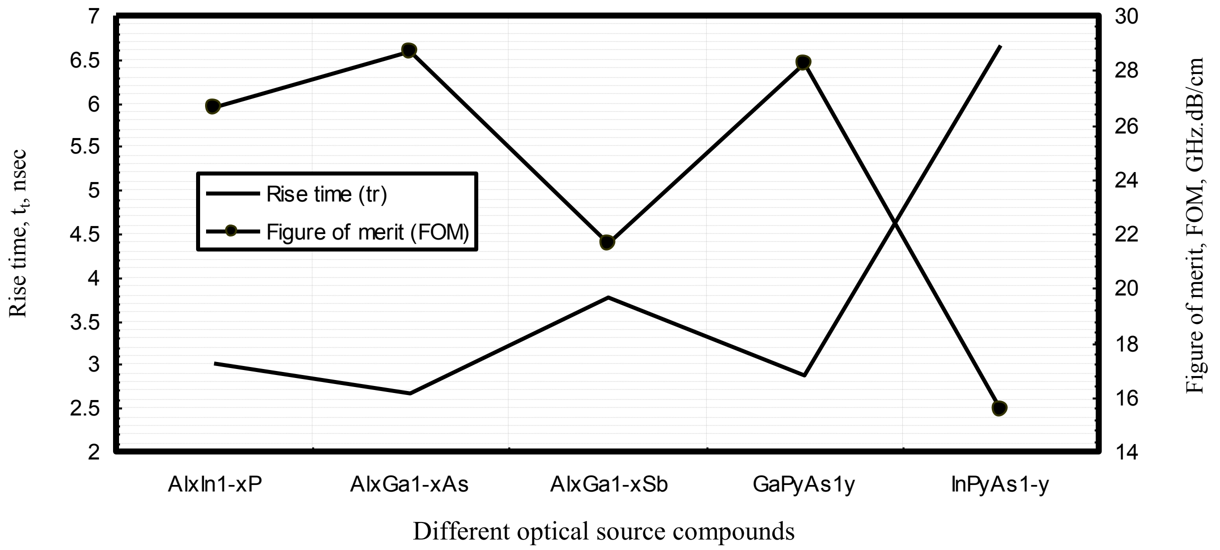

Fig. 4. Rise time and figure of merit against different optical sources compounds without any dopant ratio added in room temperature environment ($T=T_0=300$ K) at the assumed set of the operating parameters.

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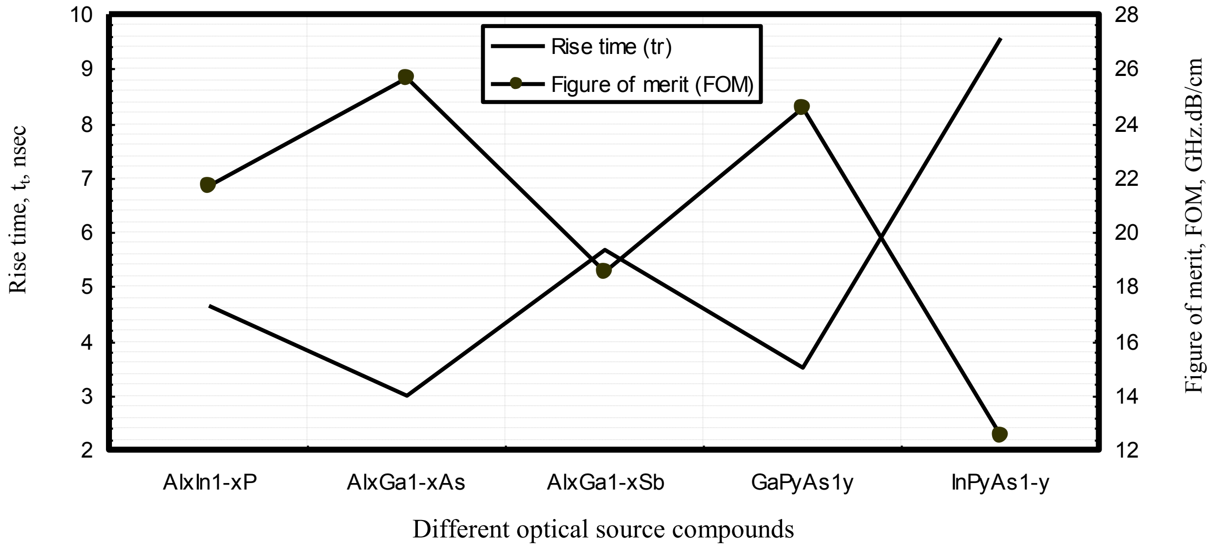

Fig. 5. Rise time and figure of merit against different optical sources compounds without any dopant ratio added in ambient temperature environment (T=350 K) at the assumed set of the operating parameters.

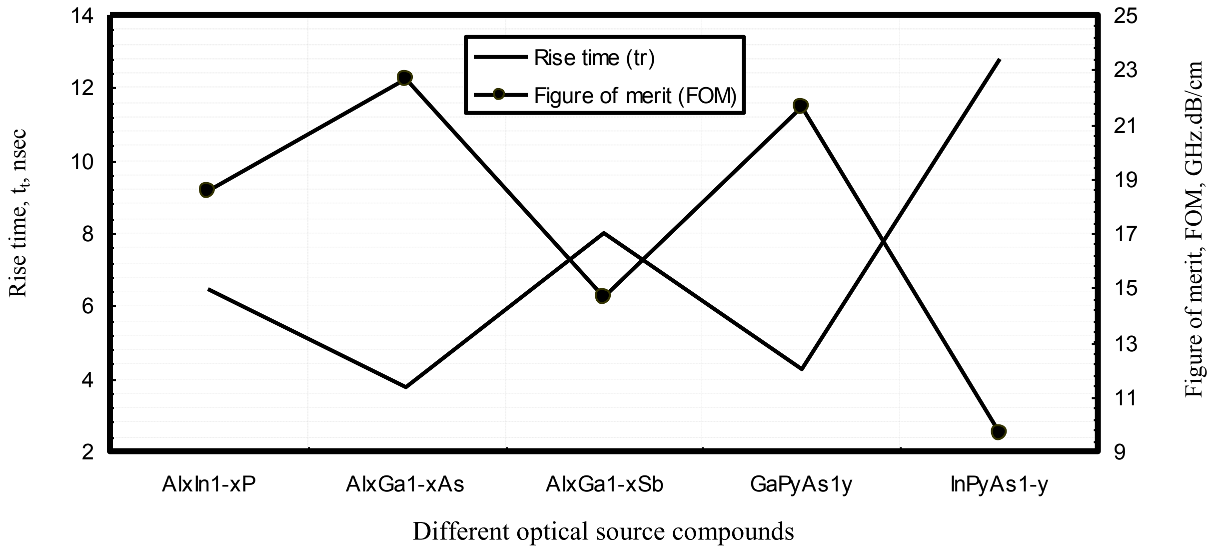

Fig. 6. Rise time and figure of merit against different optical sources compounds without any dopant ratio added in ambient temperature environment (T=400 K) at the assumed set of the operating parameters.

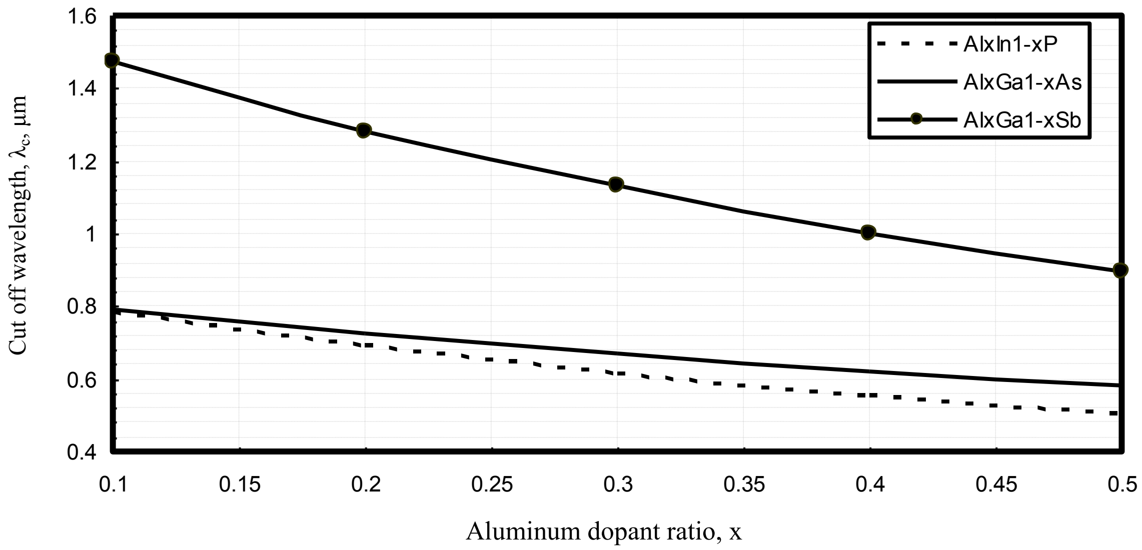

Fig. 7. Cut off wavelength for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

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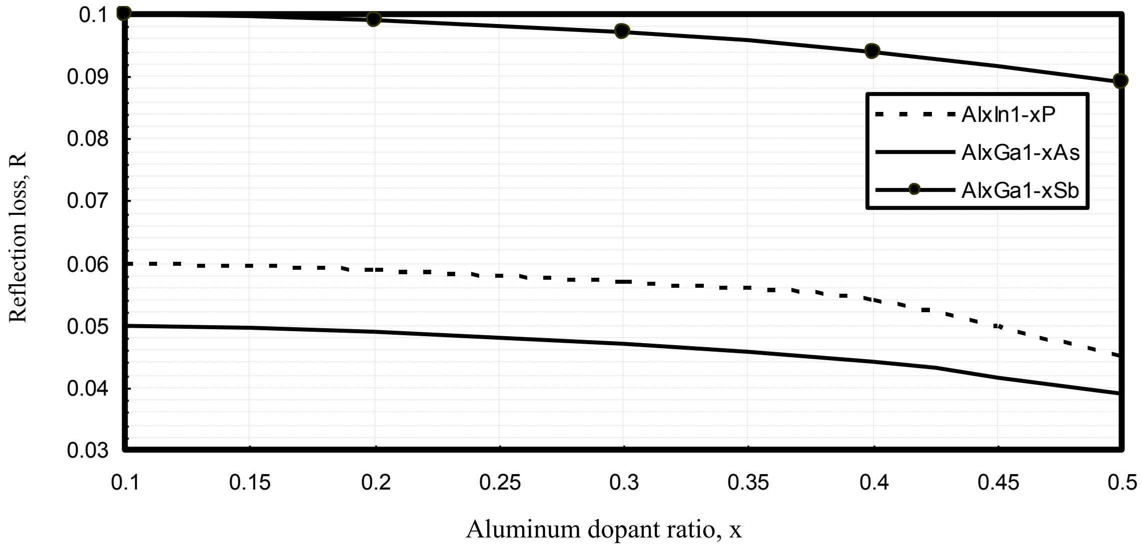

Fig. 8. Reflection loss for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

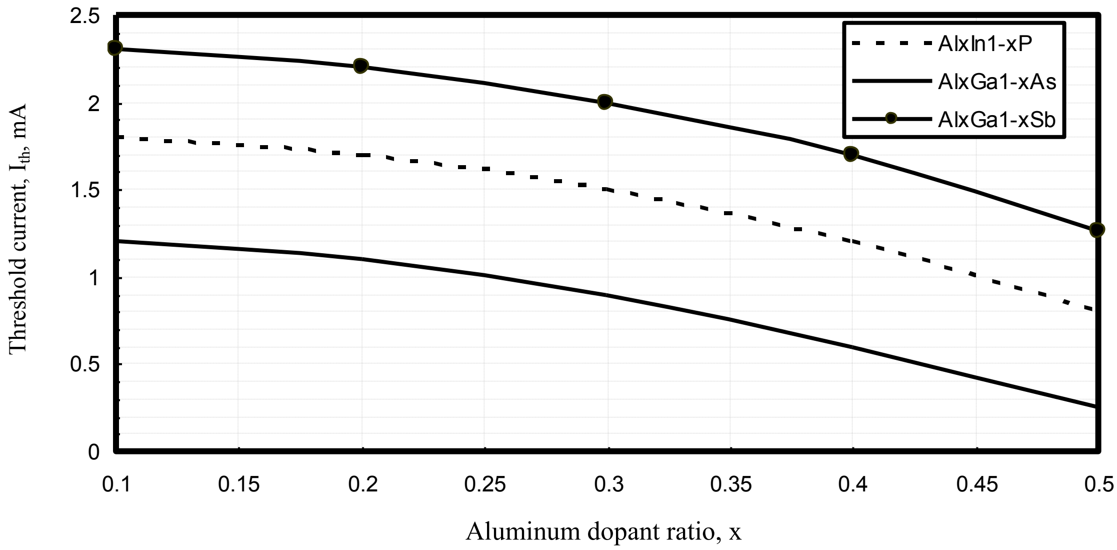

Fig. 9. Threshold current for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

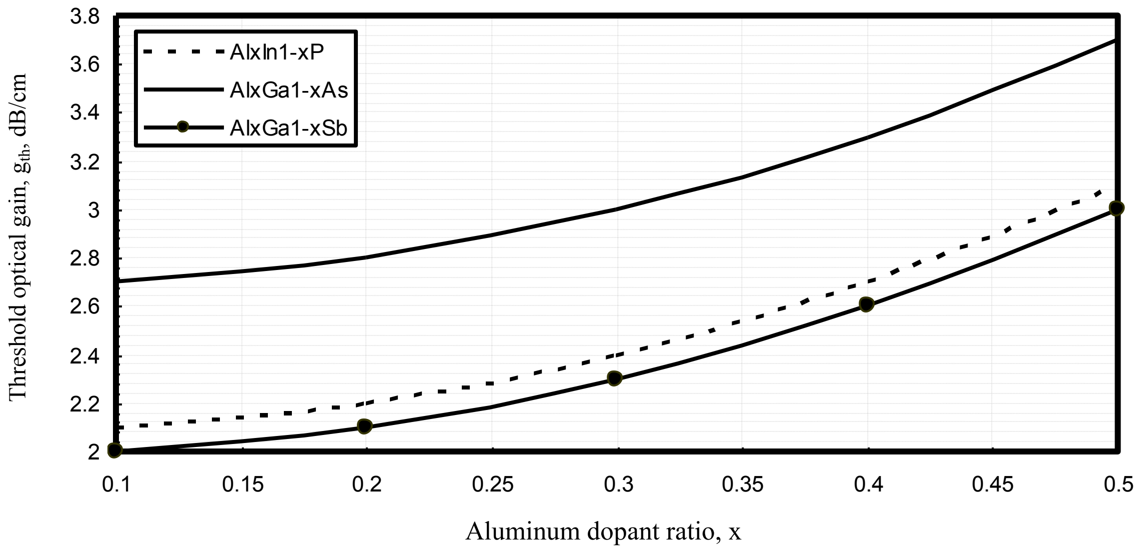

Fig. 10. Threshold optical gain for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

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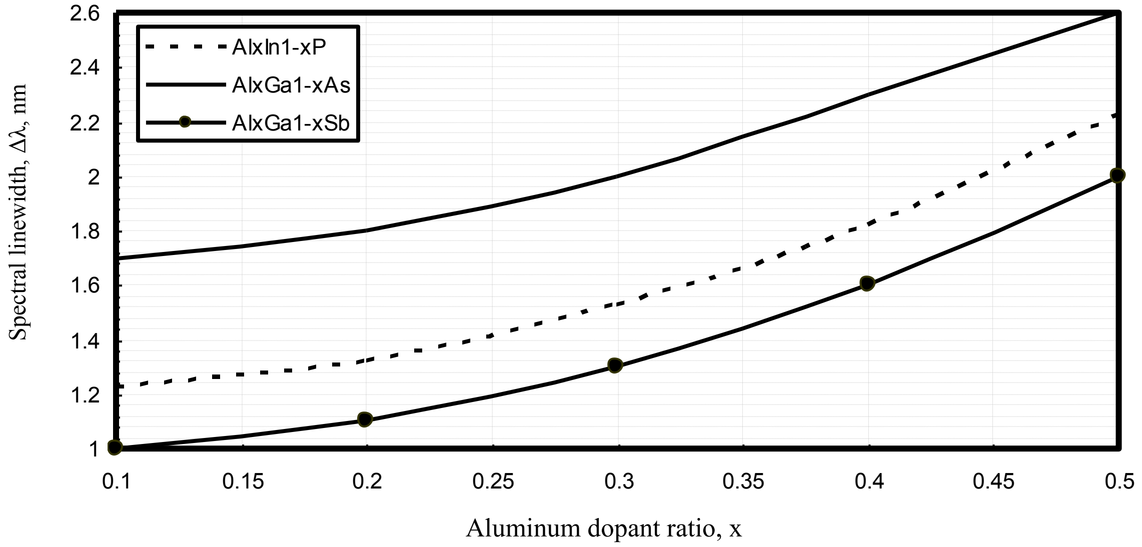

Fig. 11. Spectral linewidth for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

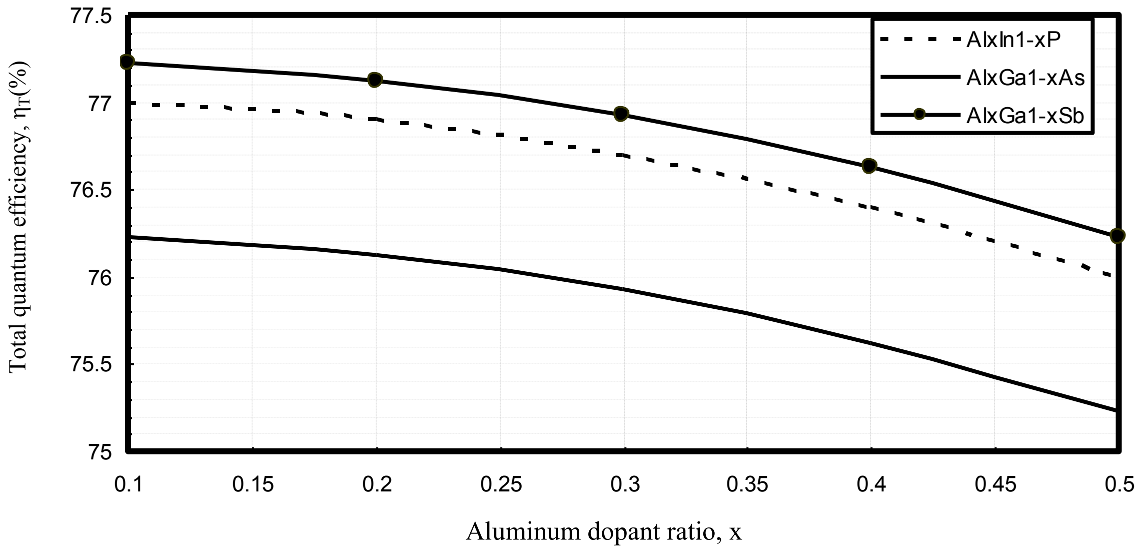

Fig. 12. Total quantum efficiency for different optical sources compounds in relation to aluminum dopant ratio at the assumed set of the operating parameters.

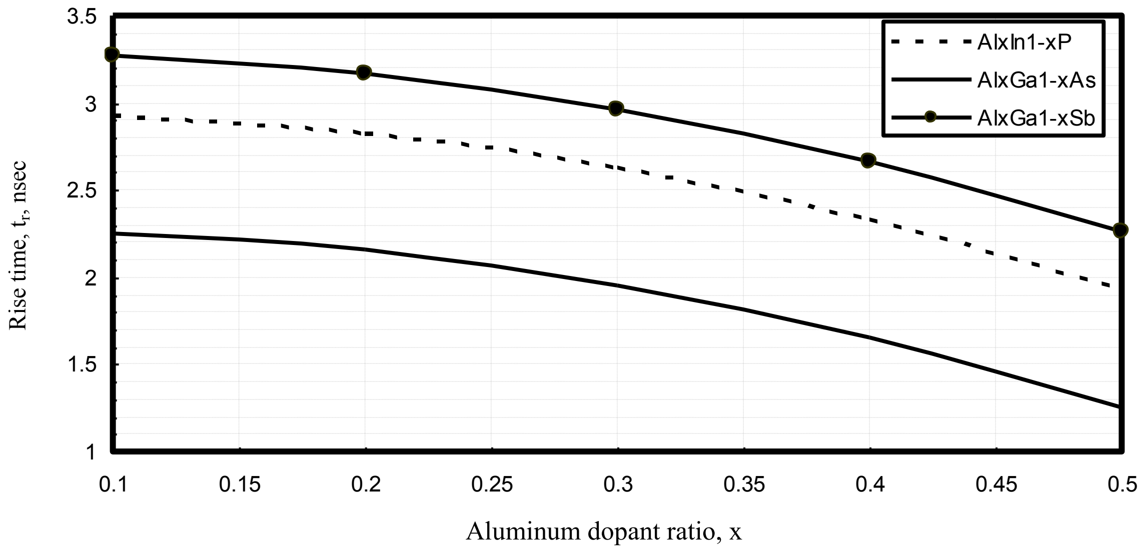

Fig. 13. Rise time for different optical sources compounds in relation to aluminum dopant ratio in room temperature environment ($T=T_0=300$ K) at the assumed set of the operating parameters.

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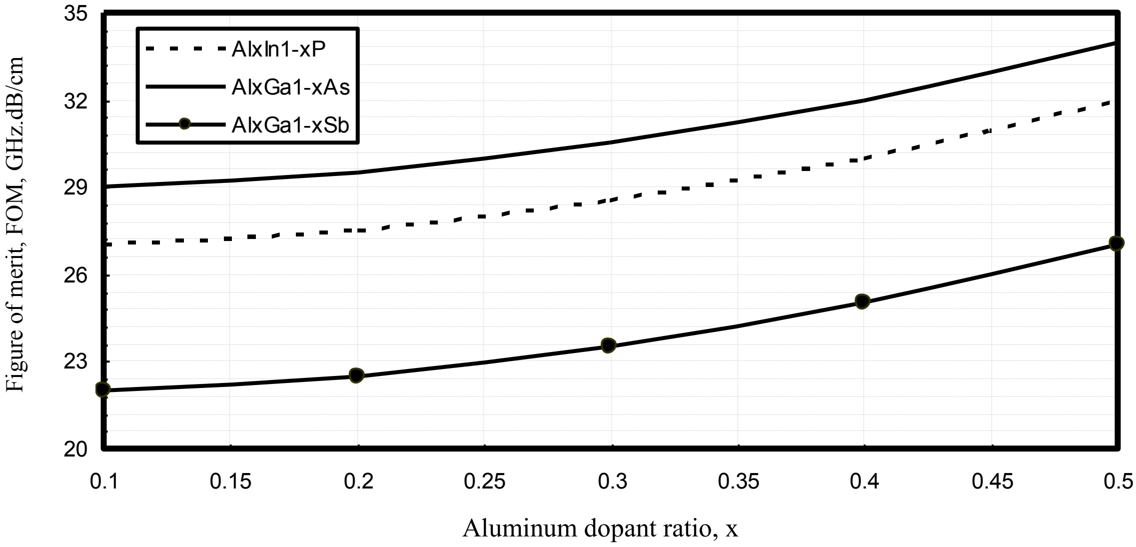

Fig. 14. Device figure of merit for different optical sources compounds in relation to aluminum dopant ratio in room temperature environment ($T=T_0=300$ K) at the assumed set of the operating parameters.

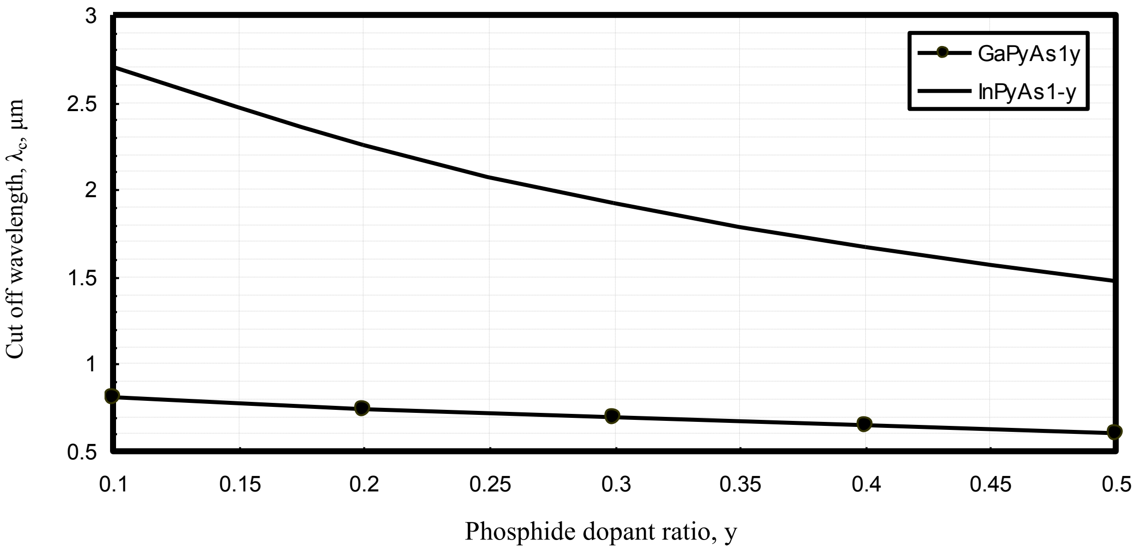

Fig. 15. Cut off wavelength for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

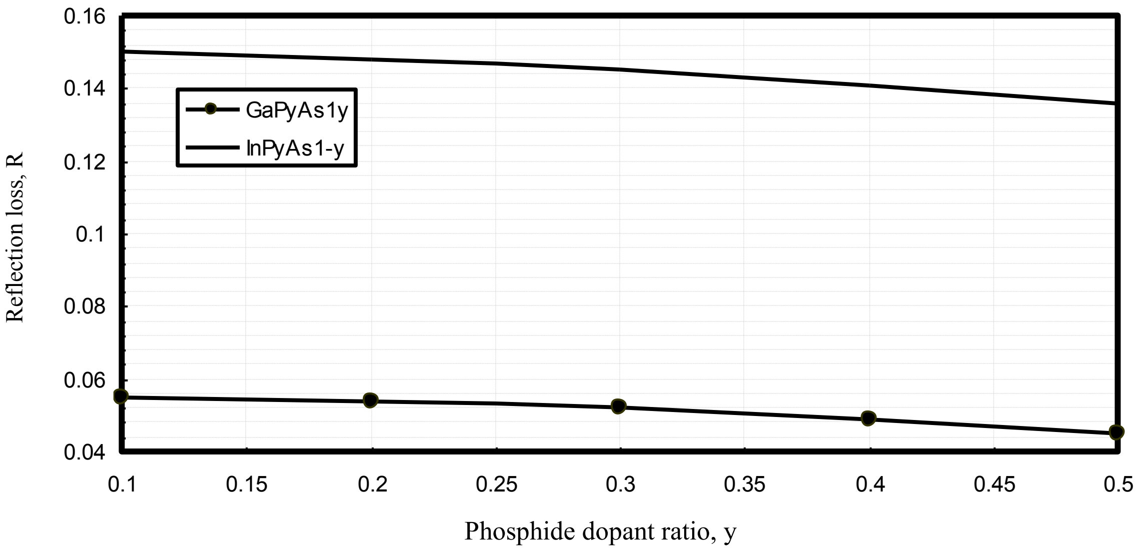

Fig. 16. Reflection loss for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

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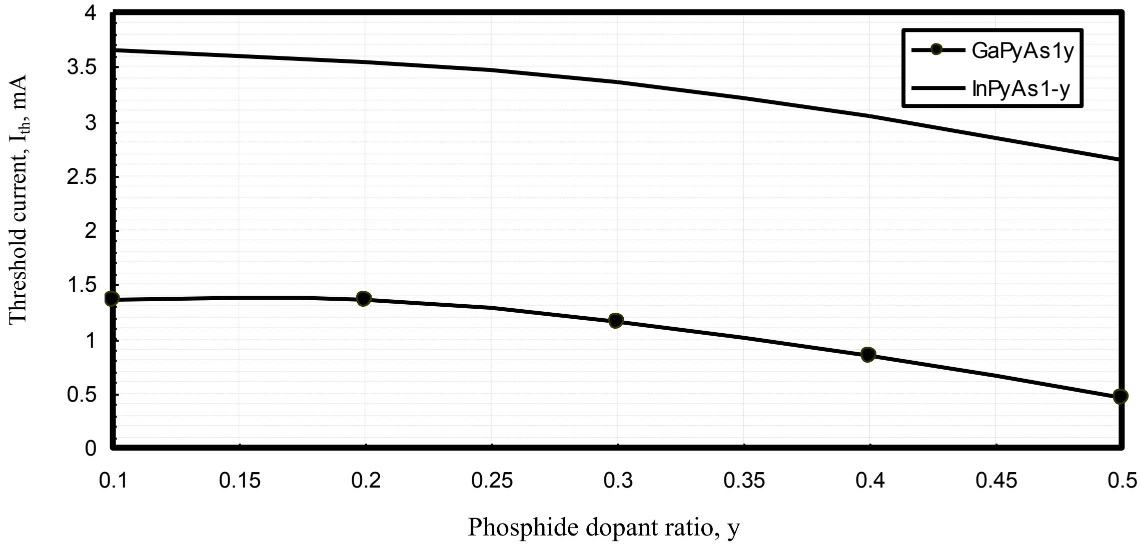

Fig. 17. Threshold current for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

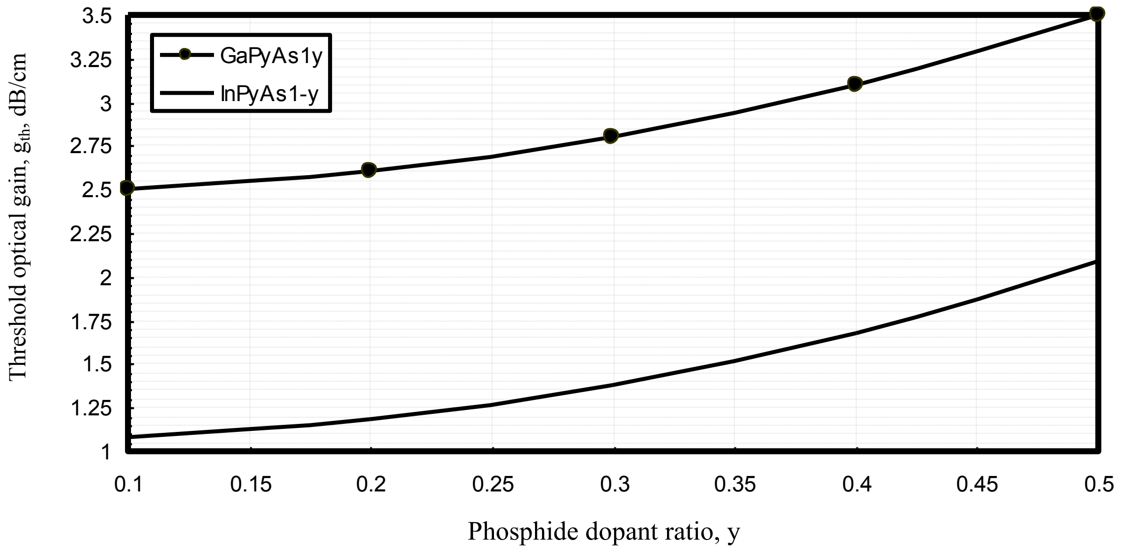

Fig. 18. Threshold optical gain for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

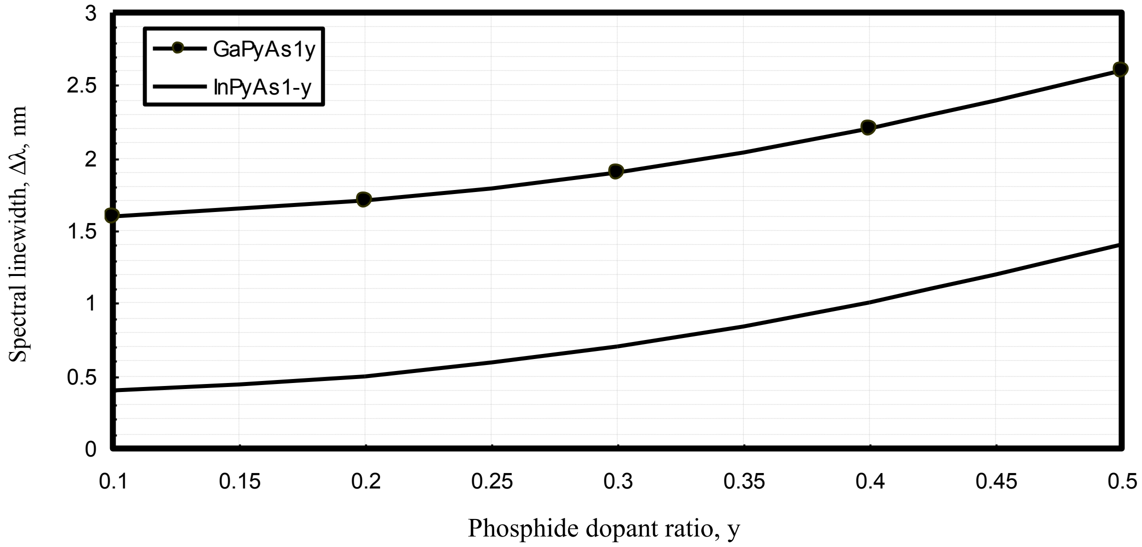

Fig. 19. Spectral linewidth for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

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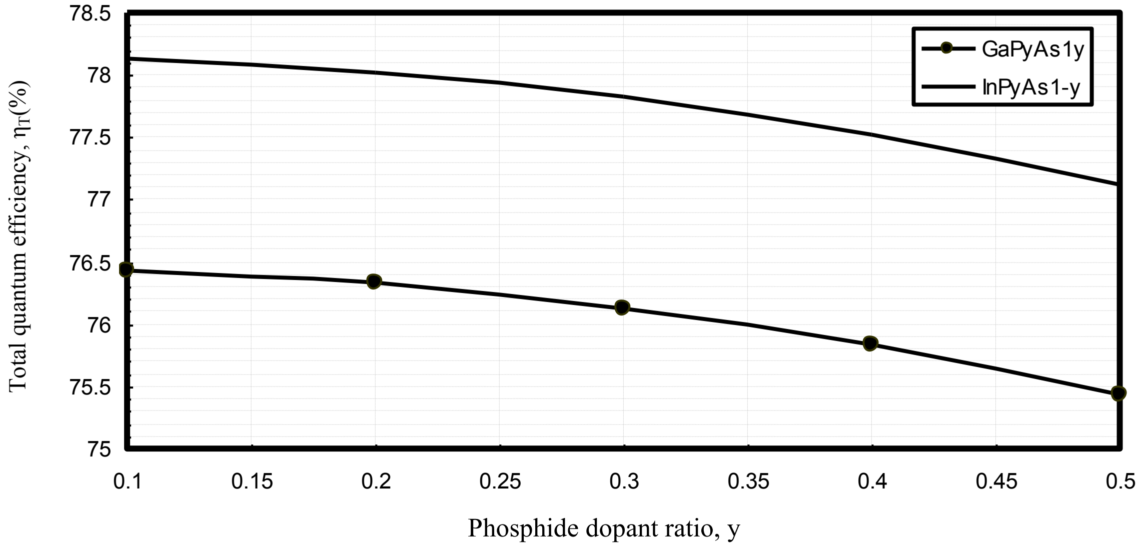

Fig. 20. Total quantum efficiency for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

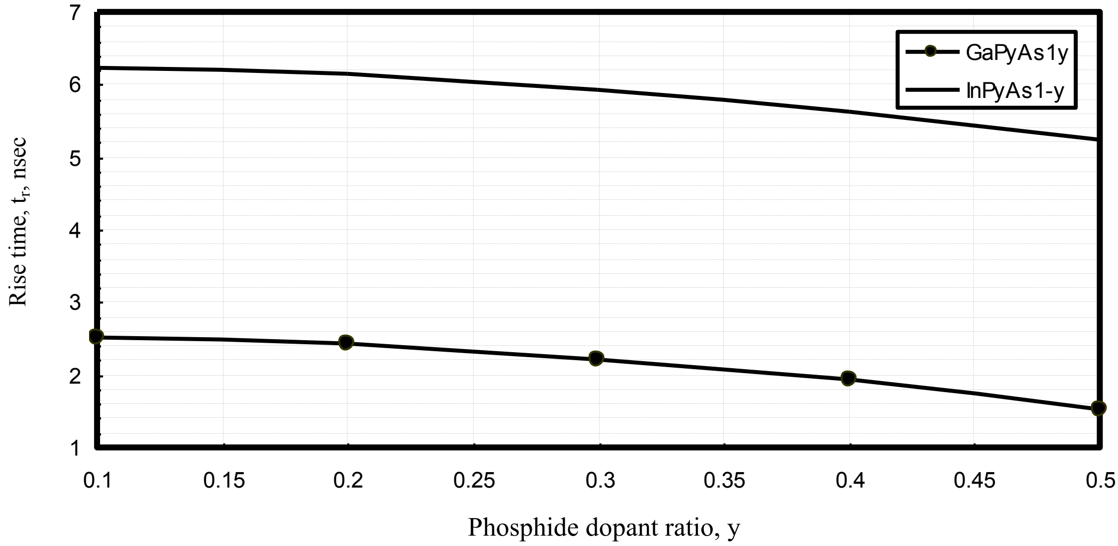

Fig. 21. Rise time for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

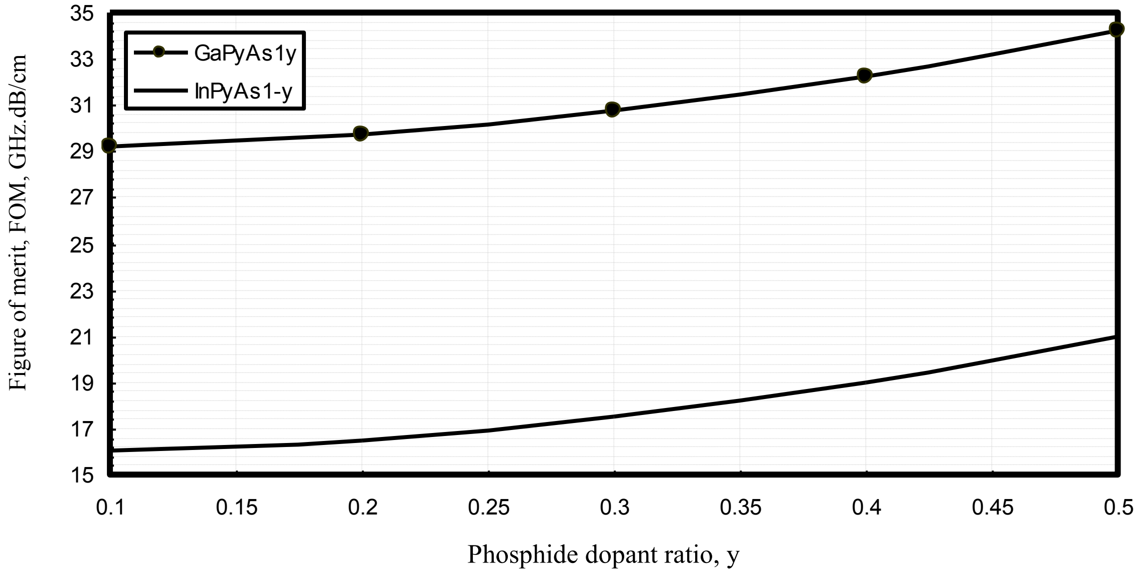

Fig. 22. Device figure of merit for different optical sources compounds in relation to phosphide dopant ratio at the assumed set of the operating parameters.

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xi) Figs. (19, 20) have assured that spectral linewidth slightly increases and total quantum efficiency slightly decrease with increasing phosphide dopant ratio for different optical laser diode sources compounds and under the same operating considerations.

xii) As shown in Figs. (21, 22) have indicated that rise time decreases and optical laser diode sources figure of merit increases with increasing phosphide dopant ratio for different optical laser diode sources compounds and under the same operating considerations and room temperature effects.

IV. CONCLUSIONS

In a summary, we have investigated the speed of operation and transmission operation performance efficiency of different Optical laser diode sources under thermal effects and different aluminum and phosphide doping levels. It is theoretically found that the dramatic effects on the optical laser diode sources rise time and its transmission efficiency. As well as it is indicated that the increased aluminum and phosphide dopant levels, this results in the increased threshold optical gain and device figure of merit. Moreover it is observed that the increased dopant levels, this leads to the decreased threshold current, reflection loss, and device rise time which results in the increased device bandwidth. We have summarized the efficient effects of added aluminum and phosphide dopant levels on the performance parameters and transmission operation performance efficiency for different optical laser diode sources compounds as listed in Table 2, 3 below.

Table 2: Efficient effects of added aluminum dopant ratio on the performance parameters of optical laser sources.

Performance parameters	Best operating conditions {room temperature T_0=300 K, and operating optical signal wavelength λ=1.55 μm}											
	Without any dopant added			With aluminum dopant added								
	$Al_xIn_{1-x}P$	$Al_xGa_{1-x}As$	$Al_xGa_{1-x}Sb$	$Al_xIn_{1-x}P$			$Al_xGa_{1-x}As$			$Al_xGa_{1-x}Sb$		
				0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
Reflection loss (R), %	6.3	5.3	10.5	6	5.7	4.5	5	4.7	3.9	10	9.7	8.9
Threshold current (I_{th}), mA	1.865	1.265	2.354	1.8	1.5	0.8	1.2	0.9	0.256	2.3	2	1.26
Optical threshold gain (g_{th}), dB/cm	2	2.654	1.654	2.1	2.4	3.1	2.7	3	3.7	2	2.3	3
Rise time (t_r), nsec	3	2.665	3.765	2.925	2.625	1.925	2.25	1.95	1.25	3.26	2.96	2.26
Figure of merit (FOM), GHz.dB/cm	26.54	28.65	21.23	27	28.5	32	29	30.5	34	22	23.5	27

Table 3: Efficient effects of added phosphide dopant ratio on the performance parameters of optical laser sources.

Performance parameters	Best operating conditions {room temperature T_0=300 K, and operating optical signal wavelength λ=1.55 μm}							
	Without any dopant added		With phosphide dopant added					
	GaP_yAs_{1y}	InP_yAs_{1-y}	GaP_yAs_{1y}			InP_yAs_{1-y}		
			0.1	0.3	0.5	0.1	0.3	0.5
Reflection loss (R), %	5.8	15.64	5.5	5.2	4.5	15	14.5	13.6
Threshold current (I_{th}), mA	1.365	3.654	1.36	1.15	0.45	3.65	3.35	2.65
Optical threshold gain (g_{th}), dB/cm	2.453	0.9765	2.5	2.8	3.5	1.08	1.38	2.05
Rise time (t_r), nsec	2.8765	6.654	2.523	2.223	1.52	6.234	5.93	5.24
Figure of merit (FOM), GHz.dB/cm	28.23	15.543	29.23	30.75	34.3	16	17.5	21

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