

Influence of mode confinement factor on the modulation properties of the Vertical Cavity Surface Emitting VCSEL laser

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Abstract

Vertical cavity surface emitting laser VCSEL is currently the main solution for many technological aspects, ultrafast optical interconnecting, Gigabit Ethernet, etc. In this paper we present the simulation results by using Optiwave™ software version 7, of the effects of optical mode confinement factor on the modulation properties (which inspected by eye diagram of the received signals) of the vertical cavity surface emitting laser VCSEL, with the range (8-20)Gbps of pseudo random bit sequence PRBS. The quality of the VCSEL modulation have been inspected by time domain signals, spectrums and eye diagram. Simulation results appeared an improvement in the characteristics of received bit sequences of (8, 10, 12.5, 16 and 20) Gbps bit rates, represented by the rising the value of quality factor QF (1.77 to 4.81) versus increasing the value of optical mode confinement factor Γ (0.2 to 0.5) respectively, and a decreasing in jitter time of superimposed traces of eye pattern and well opening eye pattern. And in the corresponding, the bit error rates BERs of the received signals have been decreased, with rising the value of mode confinement factor Γ of the laser at constant modulation index and constant temperature of the laser. Also, the VCSEL's modulation response differences with different bitrates, causes different values of QF and BER for individual value of mode confinement factor Γ .

Keywords: Semiconductor laser, optical communication, optical modulation, VCSEL, rate equations

تأثير معامل الحصر الضوئي على خصائص تضمين ليزر الانبعاث السطحي ذي الفجوة العمودية VCSEL

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الخلاصة:

تعتبر ليزرات الانبعاث السطحي ذي الفجوة العمودية حلاً للعديد من الجوانب التكنولوجية مثل أنظمة الربط الضوئي وأنظمة الإيثرنت ذات البيانات في حدود عالية جداً كأنظمة الإيثرنت ذات البيانات في حدود الكيكايت وغيرها. في هذا البحث قمنا بدراسة استقصائية ومحاكاة حاسوبية من خلال استخدام برنامج الـ *optisys7™ software* لتأثير عامل الحصر الضوئي لنمط ليزر الانبعاث السطحي ذي الفجوة العمودية على خواص التضمين للإشارة من نوع البيانات الشبه عشوائية وبمعدل بتات ضمن المدى (8-20)Gbps. وتم اختبار التضمين من خلال فحص اشارات المجال الزمني والطيف الضوئي للإشارات المضمنة والطيف الراديوي للإشارات المستلمة وكذلك تم فحص جودة الإرسال من خلال اختبار نمط العين. حيث أظهرت نتائج المحاكاة تحسناً كبيراً في نمط العين من خلال زيادة فتحة العين وتقليل عرض الارتعاش الناتج عن تراكب البتات المستلمة والمكونة لنمط العين وكذلك لوحظ تحسن للبتات المستلمة من خلال زيادة عامل النوعية للبتات المستلمة مع زيادة معامل حصر النمط وفي المقابل لوحظ تناقص نسبة الخطأ في البت للإشارات المستلمة وذلك عند زيادة عامل حصر النمط الضوئي لليزر، وذلك عند قيمة ثابتة من معامل التضمين m وثبتت درجة حرارة الليزر. وجد ان قيم عامل النوعية ومعامل

خطأ البت تتغير أيضا بتغير معدل تضمين الليزر عند قيمة نفس القيمة من عامل حصر النمط الضوئي Γ وذلك بسبب اختلاف استجابة الليزر مع سرعة معدل البيانات المضمنة.

الكلمات المفتاحية: ليزر شبه الموصل، الاتصالات الضوئية، التضمين المباشر، ليزر الانبعاث السطحي، معادلات المعدل

1. Introduction

During the past three decades, vertical cavity surface emitting lasers VCSEL, became the powerful tool in utilizing in many technology fields [1], e.g. over 10Gb/s data rate transceiver fiber optic communications [2][3], avionic Gigabit full duplex Ethernet [4], high resolution-fast printers [5], high performance computing (HPC) hardware [6] biomedical imaging and sensing [10]. These applications and else other, are the results of unique features of VCSEL, such as low producing costs, ultra-fast response, high temperature stability, spectral purity and other features, in comparing with the edge emitting laser(EEL). The revolutionary developments in the information technology(IT), cloud computing and cloud storage, internet of things (IOT) and the huge growth of internet users, increased the demands on expanding internet protocol (IPV6), which in turn pushed the researchers to provides ultrafast devices for processing, routing and transmission hundreds of Giga bits or Tera bits per seconds data rates and covering next generation all optical signal processing, for these reasons, VCSEL represent one of the promising solutions[5]. VCSEL modulation issue have been intensively reported[7][8][9]. Among the many parameters of VCSEL, mode confinement factor plays crucial role in modulation characteristics[11]. In this research, we proposed direct modulation of VCSEL with many Gbps bitrate of the non-return to zero(NRZ) pseudo random bit sequence PRBS signals and investigating by the simulation using Optiwave™ software, the influence of the mode confinement factor on the modulation characteristics, e.g. on time domain signal, modulated carrier spectrum and received eye diagrams.

2. VCSEL's dynamical Model

The optical output of the VCSEL is governed by single mode rate equations for both carrier numbers and photon numbers, which can be written [12]

$$\frac{dN}{dt} = \frac{\eta_i I}{e N_w} - (A + BN). N - GS + F_N(t) \quad \dots\dots(1)$$

$$\frac{dS}{dt} = \Gamma \beta B N_w N^2 + N_w GS - \frac{S}{\tau_p} + F_S(t) \quad \dots\dots(2)$$

Where G is the modal gain and it is given as:

$$G = g_0 \frac{N - N_t}{1 + \epsilon S} \quad \dots\dots(3) \quad \text{and } g_0 \text{ is the gain coefficient, which is given by:}$$

$$g_0 = v_g \Gamma \frac{a}{V_{act}} \quad \dots\dots(4)$$

Where N is the carrier number, S is photon number, N_w is the quantum well number, I is the bias current, A and B are the non-radiative and bimolecular-recombination coefficients respectively. e is the electron charge, η_i is the internal quantum efficiency, τ_p is photon lifetime, β is the spontaneous emission fraction coupled to output, v_g is the group velocity, a is the differential gain, V_{act} is volume of the active layer, N_t is carrier number at transparency, ϵ is the nonlinear gain coefficient. Whereas the Langevin functions $F_N(t)$, $F_S(t)$ describe the carrier and photon numbers fluctuations respectively, which are responsible for the noise intensity in the laser, their mean values are zero $\langle F_N(t) \rangle = \langle F_S(t) \rangle = 0$, but they can be calculated in term of their spectral densities and in their inter-correlation product as follows:[11][13]

$$\langle F_N^2 \rangle = \frac{\eta I l}{e} + 2g_0 N_w \frac{N_t}{1+\epsilon S} S \quad \dots\dots(5)$$

$$\langle F_S^2 \rangle = 2g_0 N_w \frac{N_t}{1+\epsilon S} S + 2 \frac{S}{\tau_p} \quad \dots\dots(6)$$

$$\langle F_N F_S \rangle = -[2g_0 N_w \frac{N_t}{1+\epsilon S} S + \frac{S}{\tau_p}] \quad \dots\dots(7)$$

Equations (1)to (7) are embedded in the algorithms of VCSEL component in the optiwave7 software, and they are numerically solved during circuit simulation running.

3-Simulation setup

The configuration of the transmission setup constructed from VCSEL device for which directly modulated by Non-return to zero signal which in turn driven by pseudo-random bit sequence generator (PRBG) with multi Gb/s bitrates, as a modulated signal (or so called base band information signal). The optical output is directed via the loss free line to the photodetector as receiver, which converts optical signal to electrical one, to extract the base band modulated random bit sequences. The recovered bit sequence signal (time series) be monitored by the electrical oscilloscope visualizer(EOV), and its spectrum resolved by electrical spectrum analyzer(ESA). The strength of recovered bit sequence electrical signals is measured by power level meter in Decibel (dBm). A part of the optical signal output from VCSEL is monitored by optical time domain visualizer(OTDV) and its spectrum is analyzed by optical spectrum analyzer(OSA), as shown in the Fig.1. The simulation is carried out by Optiwave™ software, ver.7[14]. The bias and the modulated currents of VCSEL are adjusted according to linear part of the power-current(L-I) curve of laser VCSEL, which have been predetermined as shown in the Fig.2. We have selected the values of the bias current I_b and modulated signal current I_m in such way that the modulation index would give out optimum values for eye diagram parameters (maximum value of quality factor QF and minimum value of bit error rate), for certain values of the VCSEL optical mode confinement factor Γ , and bitrate. The parameters of VCSEL which are used in the simulation are tabulated in the Table1. Eye diagram is very helpful mean for the qualitative analysis used in fast digital transmission, it is an oscilloscope display of digital signal, recurrently sliced to get a best acting of its behavior[15]. A traditional ways to describing an eye are to measure the rise times, fall times, jitter at the middle of crossing point of the eye, transcend present and many other characteristics of eye behavior in order to make decision about measured digital signal.[16]

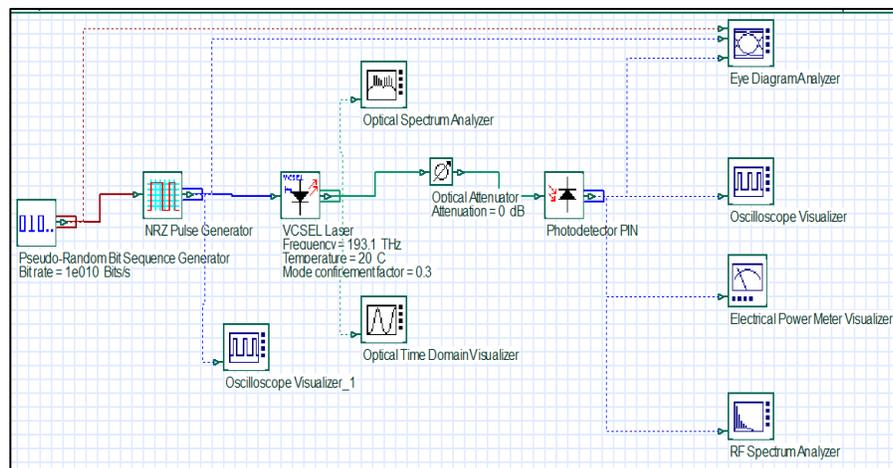


Figure 1. VCSEL optical transmitter block sets by using optiwave™ software

Table 1. VCSEL parameters[14]

Parameter	Value	Unit
Active layer Volume (V)	1.5×10^{-10}	cm^3
Group velocity (v)	8.5×10^9	cm/s
Quantum efficiency (η_Q)	0.4	
Differential gain coefficient (σ_d)	2.5×10^{-16}	cm^2
Carrier density at transparency (N_T/V)	10^{18}	cm^{-3}
Mode confinement factor (Γ)	0.1-0.5	
Gain coefficient (g)	16000	1/s
Carrier number at transparency (NT)	19400000	
Carrier lifetime (τ_C)	10^{-9}	s
Photon lifetime (τ_P)	3×10^{-12}	s
Spontaneous emission factor (β)	3×10^{-5}	
Gain compression coefficient (ϵ_m)	10^{-17}	cm^3
Linewidth enhancement factor (α)	5	
Current injection efficiency (η_{inj})	1	
Scaling factor (S)	2.6×10^{-8}	w

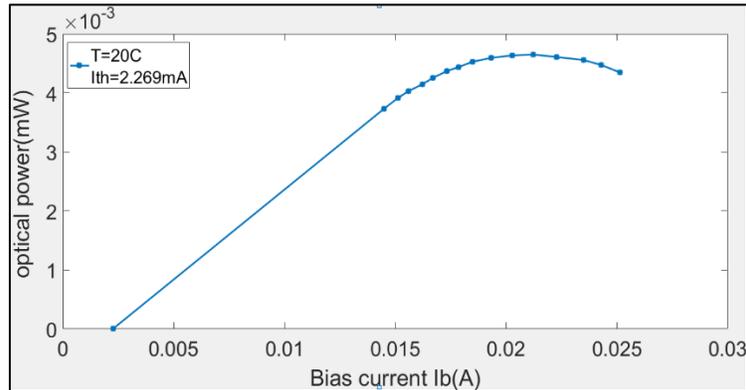


Figure 2. L-I curve of VCSEL at 20⁰C temperature[14]

4- Results and Discussion

4.1 Simulation of VCSEL transmitter

We have carried out the simulation of transmission of VCSEL modulation with different values of the modulated signal bit rates 8, 10, 12.5, 16 and 20Gbps, such that all parameters of the VCSEL been set as in Table 1. The transmission characteristics such as modulated and optical carrier signals, their spectrums,

received signal, spectrum, received power and eye diagram have been recorded. For the typical case of the simulation results of VCSEL's optical pulses, Fig. 3(a) shows time domain of 10Gbps NRZ format of base band signal produced by PRBS generator, monitored by the oscilloscope visualizer, while Fig 3(b) shows modulated optical carrier time domain signal and its spectrum in Fig3(c) resolved by the OSA, meanwhile Fig3(d) depicts the time domain of received signal and its showed by RF spectrum analyzer(SA)in the Fig3(e), and the Fig3(f) appears eye diagram of the received signal. There is clearly similarity between the optical pulses in Fig3(b) and received signal Fig3(d) and also between their spectrums Fig3(c) and Fig3(e). That is because of the connection between transmitter and the receiver take place via loss free transmission medium, which prevent the transmitted signals from the losses distortion.

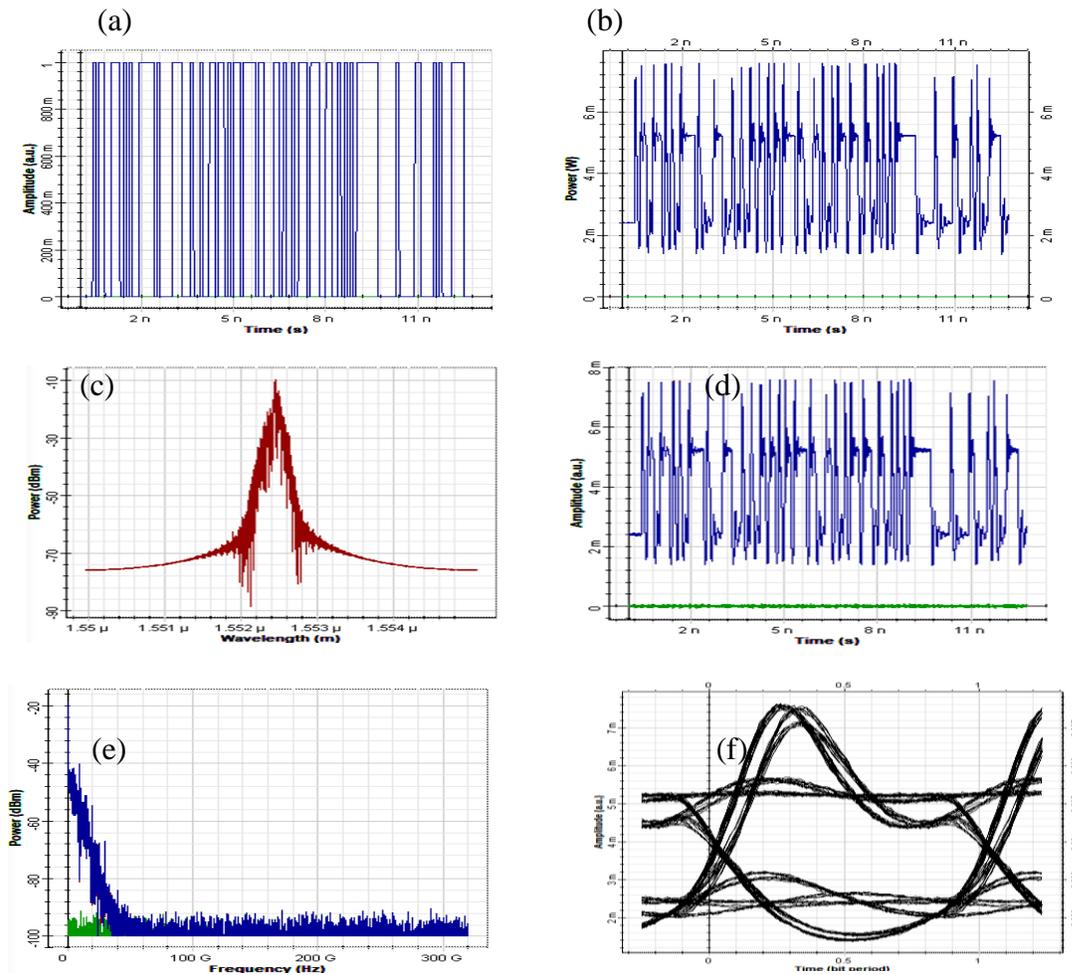


Figure 3. Modulation of VCSEL with $\Gamma=0.5$, and data rate 10Gbps NRZ pulses, the characteristics illustrated by: (a) baseband PRBS time series, (b) modulated optical pulses (c)spectrum of modulated optical carrier , (d) received PRBS signal, (e)RF spectrum of received signal, (f) eye pattern of received PRBS signal

4.2 Impacts of optical confinement factor Γ on VCSEL transmission

In order to investigate the role of the optical confinement factor Γ on the modulation characteristics of VCSEL, the value of Γ is changed on each new program execution with the rest other parameters of the

VCSEL and bitrate being fixed. The eye pattern. Fig(4) shows the influence of optical confinement factor Γ on the eye diagram patterns, for the case of modulating VCSEL transmitter with 20Gbps NRZ pseudorandom pulses. Fig(4a) exhibits well opened eye diagram corresponds to the case of mode confinement factor ($\Gamma=0.5$), the calculated quality factor QF is 4.81 and bit error rate BER is 7.588×10^{-7} , the bolded border of eye pattern is due to the distortion arises from Langevin noise caused by spontaneous emission which coupled with laser output[9]. Simulation results of VCSEL transmitter for the case of ($\Gamma=0.4$) be shown in the Fig(4b), the height of eye pattern of received signal will have decreased and its border's thickness gradually increased, the evaluated QF is 3.11 and its BER is 0.00088. The simulation results for ($\Gamma=0.3$) appears in Fig.4(c) which displaying dense jitter of eye pattern border and the QF of the signal reduced to 2.181 and BER significantly increased to 0.0135 while the eye height drops to - 0.00142. The simulation results for the case of $\Gamma = 0.2$ is given by the Fig4(d) which appear as overlapped traces, that is due to increasing of inter-symbol interference (ISI) and hence increasing the jitter and bit error rate BER to reach to 0.0349. On the other hand, the value of the quality factor QF decreases to 1.7694.

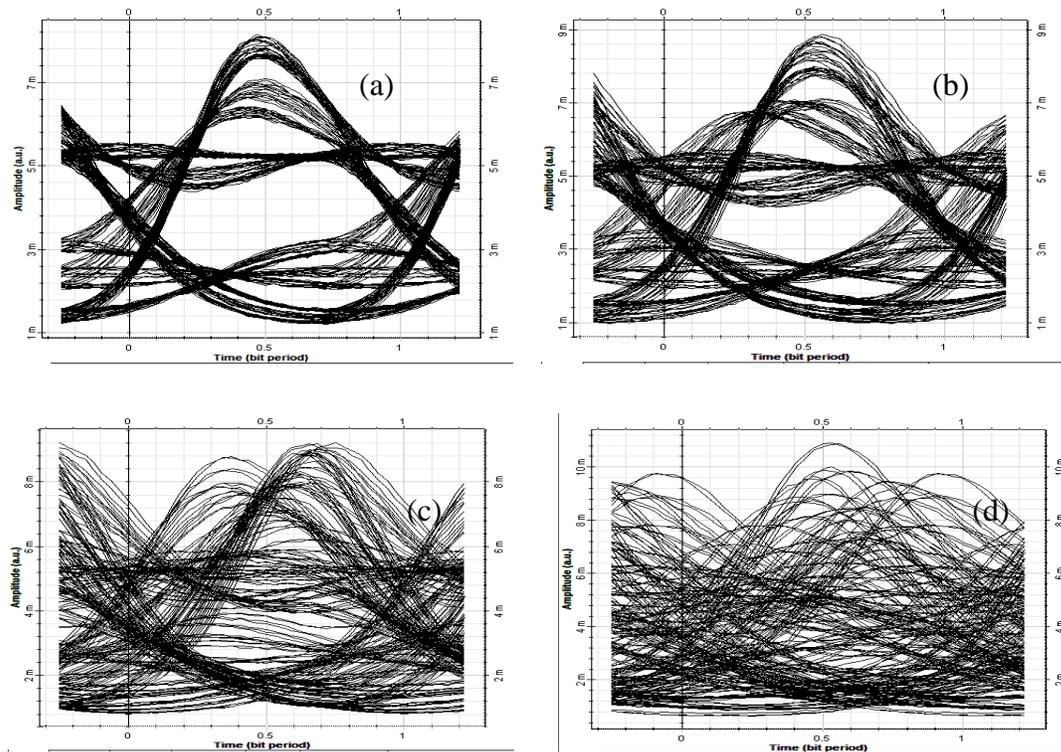


Figure 4. Effects of optical confinement factor values on Eye diagrams features for received 20Gbps NRZ format of PRBS data, modulated on VCSEL transmitter (a) $\Gamma=0.5$, (b) $\Gamma=0.4$, (c) $\Gamma=0.3$ and (d) $\Gamma=0.2$

In the previous cases of reduction modulation characteristics (decrement of QF and increasing BER) with decreasing Γ , attributed to reduction the bandwidth of VCSEL with decreasing the mode confinement factor Γ [11]. A remarkable thing was that when the value of Γ decreased, the strength of the received signal increased. Fig.5 explains the influence of mode confinement factor Γ on the quality factor QF of

the received signal for different values of data rate transmission, as it can be seen the QF increases versus raising the value of the Γ factor. Whereas in Fig.6 the BER of received signals reduced with increasing mode confinement factor Γ for different data rate values. It's important to notice that the differences among the curves of Fig(5) and Fig(6), arises from differences of the laser modulation response for the different bitrates, and hence the differences in the values of QF and BER for individual value of Γ for different values of bitrates.

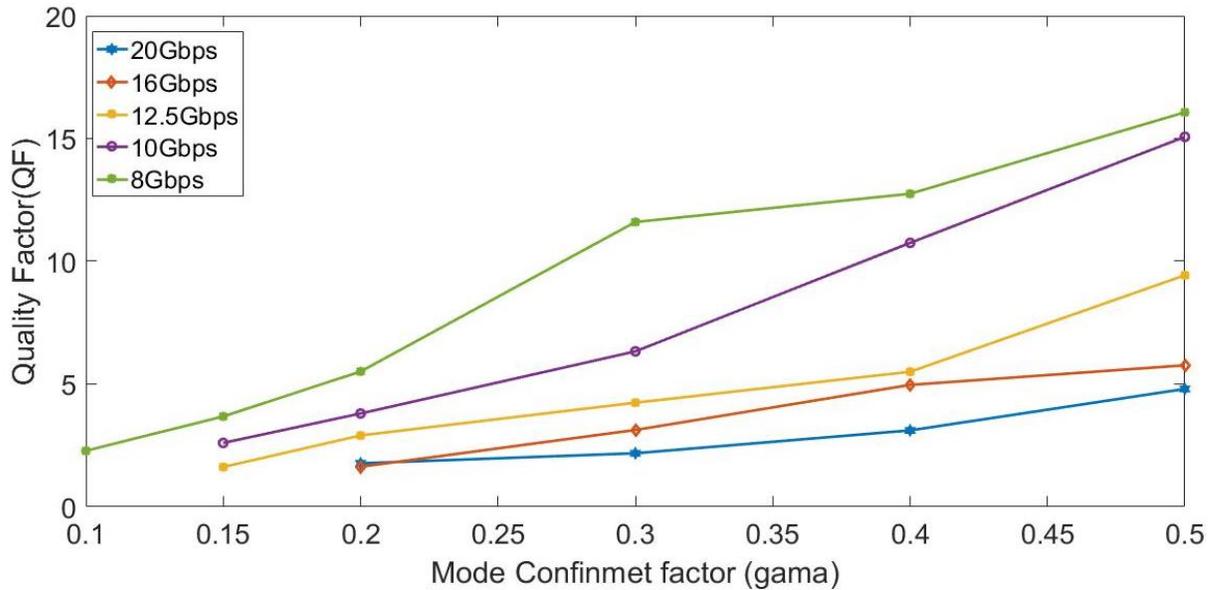


Figure 5 quality factor(QF) of received signals as a function of mode confinement factor Γ for different bitrates transmission

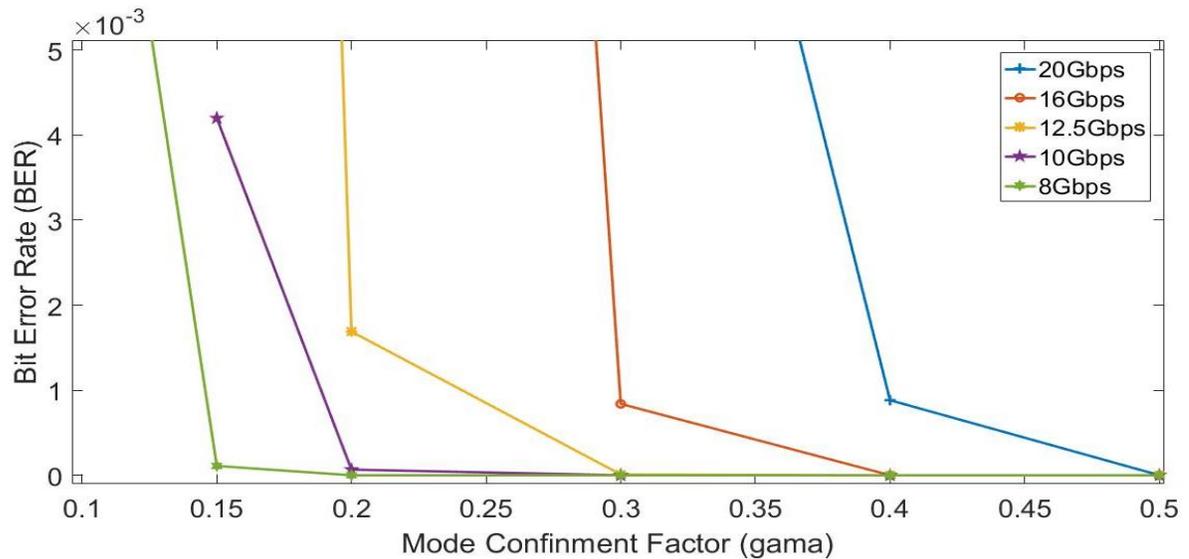


Figure 6 influence of mode confinement factor Γ on the bit error rate BER of different bitrate transmission

5. Conclusion

In summary, we have investigated by the simulation of the Optiwave™ software, the role of optical mode confinement factor Γ on the modulation characteristics (pattern of the Eye diagram), for the vertical cavity surface emitting laser VCSEL, with different values of bitrates. Eye patterns of the received signals have been highly improved by increasing mode confinement factor, especially at high data rates. This have been verified by increasing quality factor QF from 1.77 to 4.8 corresponding the increment of Γ from 0.2 to 0.5, with bitrate of 20Gbps. In the same manner, increasing the value of mode confinement factor Γ from 0.2 to 0.5, would decrease the value of the bit error rate BER of the received data sequence, from 0.0035 to 7.6×10^{-7} . Therefore, The higher the optical confinement factor, the higher the laser modulation bandwidth and the higher frequency response speed, in addition, the modulation response differences with different bitrates, caused different values of QF and BER for individual value of mode confinement factor Γ .

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7. References

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