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The output dynamics of mutually coupled semiconductor face to face laser systems under noise effect

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Abstract:

We have explored the dynamics of fields from two synchronized face- to- face lasers in the presence of noise. The study was carried out under the effect of coupling strength between the two systems, line-width enhancement factor and injection current density. All these factors affect the dynamics of temporal variation of fields from both lasers. Regions of amplitude death occurs within chaotic regions as a result of increasing of injection current density and coupling strength.

Keywords:Semiconductor lasers,Synchronization, Feedback, Chaos, Amplitude death.

Introduction:

Synchronization phenomenon is widely observed in nature and in artificial systems. The first description of synchronization is believed to have been made by Huygens. He observed that two pendulum clocks suspended in the same wooden beam tend to synchronize in opposite swings. Systems of coupled semiconductor lasers (SCLs) are receiving increasing interest, because of their practical importance for achieving high output power or for on- chip integrated optical devices. Moreover, they are important examples for coupled oscillators in general [1]. The spatial separation of the lasers always results in a time delay in the coupling due to finite signal propagation times. In many situations the time delay in the coupling has been neglected. In SCLs this is not justified due to their large bandwidth and fast time scales of their dynamics [2]. It is well known that delay effects can destabilize the laser system [3]. In delay- coupled SCLs this may even result in chaotic dynamics [4]. On the other hand, time delay in the coupling can also be used to stabilize a chaotic system [5].This character of delayed coupling makes this field attractive for fundamental investigations. Furthermore, delay coupled SCLs are promising candidates for different technological applications, such as secure chaotic communications [6]. For the study of the synchronization phenomenon, mutually delay coupled SCLs are suitable candidates because of their compactness, low cost, and durability. Different aspects of the complex dynamics of mutually SCLs systems have been probed [7,8]. The system provides a simple and powerful tool to study the collective behavior within a wide range of control parameters space, spanned by coupling strength and the time delay in coupling [9-11].

In this work we study the dynamics of two SCLs coupled in face to face configuration under the effect of number of control parameters appeared in the dynamical model given in the next section.

Theoretical model:

The rate equations we used in this work are based on the well-known Lang-Kobayashi equations for SCL with delayed feedback [12]. Such model was rewritten once more by Erzgraber et al [13]. It consists of four equations, two for the field of each laser and two for the population inversion in the same lasers. Figure (1) shows schematically the basic components of the face- to- face configuration used to study the synchronization effect.

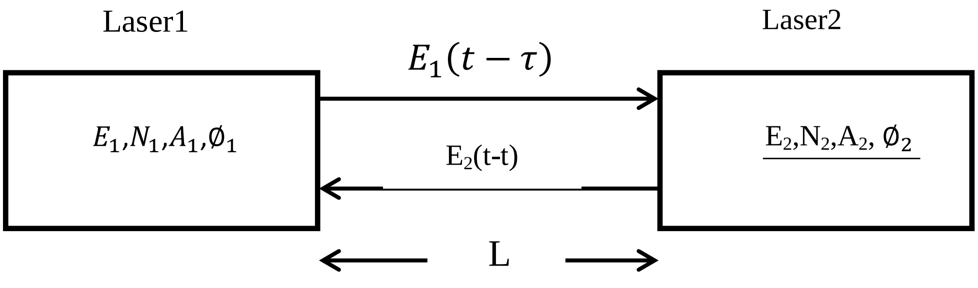


Fig. (1) Two semiconductor lasers coupled face- to- face.

By writing the field $E_{j=1,2}$ in both lasers in a complex form in terms of amplitude $A_{j=1,2}$ and phase $\emptyset_{j=1,2}$ as:

$$E_j = A_j e^{-i\emptyset_j} ,$$

the model of Erzgraberetal[13] can be written as follows:

$$\frac{dA_1}{dt} = N_1(t)A_1(t) + \eta A_2(t-\tau)\cos\left[\emptyset_1(t) - \emptyset_2(t-\tau) - \omega_2\tau\right] \quad ...(1a),$$

$T\frac{dN_1}{dt} = J_1 - N_1 - [2N_1 + 1]|A_1(t)|^2$ …(1b),

$\frac{d\emptyset_1}{dt} = -\alpha N_1(t) - \eta\frac{A_2(t-\tau)}{A_1(t)}\sin[\emptyset_1(t) - \emptyset_2(t-\tau) - \omega_2\tau]$ …(1c),

$\frac{dA_2}{dt} = N_2(t)A_2(t) + \eta A_1(t-\tau)\cos[\emptyset_2(t) - \emptyset_1(t-\tau) - \omega_1\tau]$ ...(1d),

$T\frac{dN_2}{dt} = J_2 - N_2 - [2N_2 + 1]|A_2(t)|^2$…(1e),

$\frac{d\emptyset_2}{dt} = -\alpha N_2(t) - \eta\frac{A_1(t-\tau)}{A_2(t)}\sin[\emptyset_2(t) - \emptyset_1(t-\tau) - \omega_1\tau]$ …(1f),

where:

η is the coupling strength i.e. fraction of light of one laser injected into the other and vice- versa, τ is the time taken by the light to cover distance between lasers, $\omega_{1,2}$ is the optical angular frequencies of the solitary lasers 1 and 2, N_1, N_2 are the carrier density in laser 1 and 2 respectively, α is the line width enhancement factor, $J_{1,2}$ is the injected current densities in laser 1 and 2, and T is the ratio of the carrier life time to the photon life time.The above system of equations describe the time evolution of the complex electric field $A_{1,2}(t)$ of a single longitudinal mode and carrier density $N_{1,2}(t)$ averaged over the laser medium.

To investigate the noise effect on the synchronized lasers output a term of the form $\sqrt{D_{i=1,2}\xi_{i=1,2}}$ is added to the equations (1a) (i=1) and (1d) (i=2), where $D_{i=1,2}$ are the noise strength proportional to the spontaneous emission factor, $\beta_{1,2}$, which is assumed to be the same for the two lasers. $\xi_{i=1,2}$ is a correlated white Gaussian noise having different values for both equations. The latter has the property [14]:

$<\xi_i(t)\xi_j(t')>=\delta_{ij}\,\delta(t\text{-}t')$ …(2),

Computationally this term is treated using a built in Matlab function, white Gaussian noise (wgn). We assume that its value is in the average (-1,1) at peak and the duration of the noise signal is assumed to be 10psec.

<u>Results and discussion:</u>

To obtain the sought results we solved the set of equations (1) together with equation (2), to take into account the effect of noise on the dynamics of both lasers, using Runge- Kutta numerical method and Matlab. It is clear from the system of equations (1) there exist three control parameters can affect the behavior of fields (A_1 and A_2), population inversions (N_1 and N_2) and phase of the fields ($\emptyset_1$ and $\emptyset_2$) viz coupling strength (η) between the two lasers, line-width enhancement factor (α) and injection current densities ($J_1 = J_2 = J$). These parameters were varied according to table (1).

Table (1): Control parameters values used in the calculations.

η	0	0.001	0.01	0.1	0.2	0.4
α	1.5	2.5	3.4	4.5	5	5.6
J	0.165	0.5	1	1.65	2	-

These numerical were chosen based on experimental results [1,2,6].

(i) Effect of coupling strength, η:

Figure (2) shows sample results of the effect of varying ηtwo orders of magnitude on the temporal behavior of field amplitudes A_1 and A_2 from both lasers. whenη=0, i.e. no coupling case is given for comparison. It can be seen that as η increases up to 0.01 a small variation in the fields A_1 and A_2 appeared which breaks to severe spiking in the region between transient region and the oscillatory one which tends to die as time goes on, before reaching the steady state output. The further increase inη enhances the region of instability, increases its frequency showing clear instability in the output before reaching the steady state stable output of both lasers. Attractors are generated by drawing the relation between A_1 againstA_2.The distortion in the relation among these variables indicates the instability that occurs in the output from both lasers, see figure (3).

(ii) Effect of line-width enhancement factor,α:

It is believed that line-widthenhancement factor,α, enhances nonlinearities in SCLs. In the case of synchronization of lasers, it is dependent on the coupling strength η. Figure (4) shows sample results of the effect of α on the temporal behavior of laser fields A_1 and A_2 together with attractors.

(iii) Effect of injection current,*J*:

According to the previous obtained results it seems that both signals of the field from the two lasers are identical for the low injection current density, 0.165. As the injection current density increases clear discrepancies appeared in the temporal variation of both fields from the two lasers. Various types of oscillations along each signal starting from the transient region and above appeared. Figure (5) shows the temporal variations of $A_1$and A_2. When inspecting the attractors of A_1againstA_2. (See figure (6)), we can see that this conclusion is clear where the attractors are not the same in details. Figure (7) shows the behavior of A_1 and A_2 with time as the coupling strength (η) is increased to 0.4 in comparison with figure (5) when η=0.1. The details of signals is not the same and peculiar output is generated as the injection current density reach's 2 when the output of both lasers breaks into multi chaotic signals separated by regions of dead output or death by delay extended for 250 nsec [15].Figure (8) shows the temporal variation of fields A_1 and A_2 for wide range of injection current density together with (A_1-A_2) which indicates the clear differences between each pair (A_1,A_2) of fields.

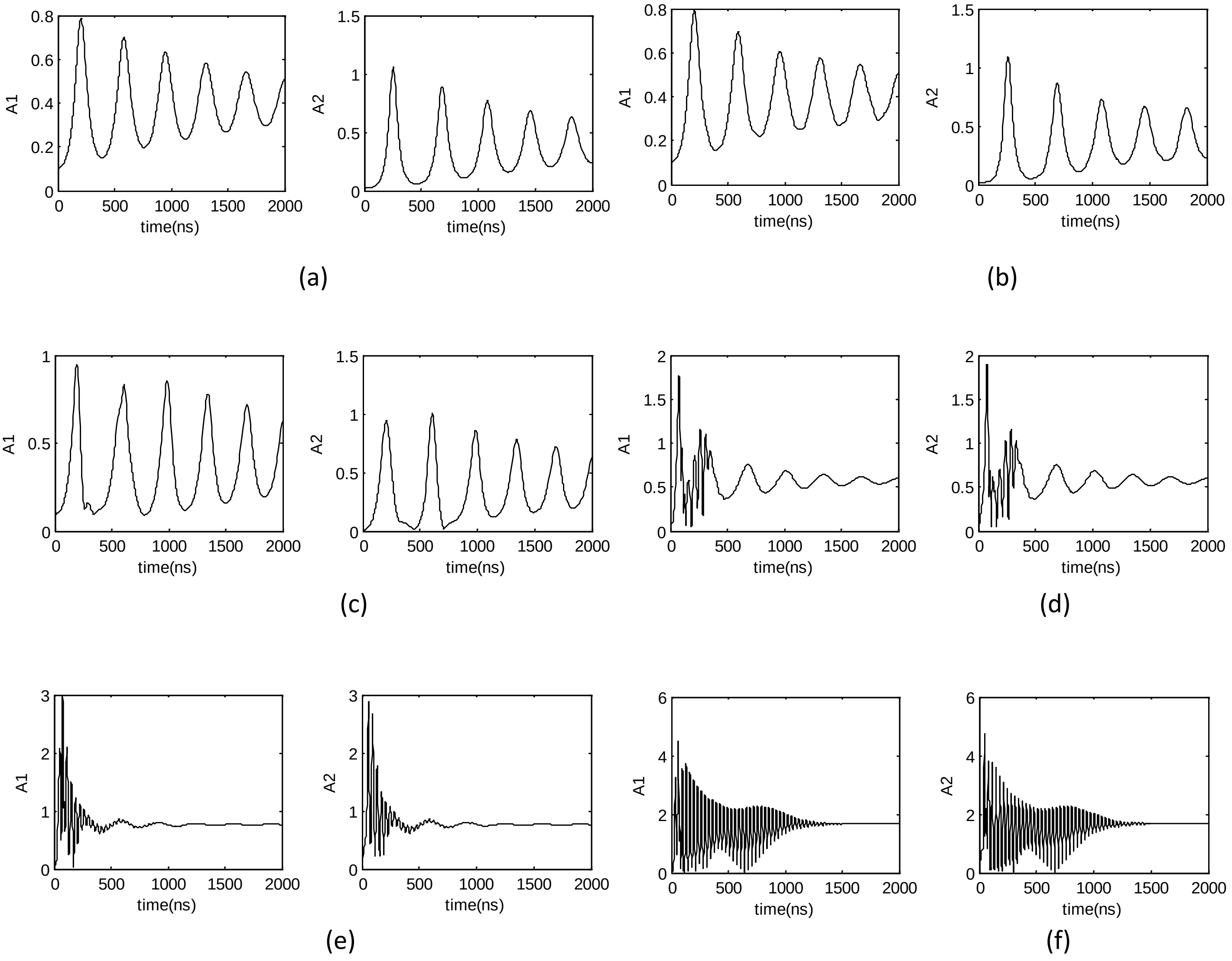
(iv) Effect of delay time,τ:

It is well known that the delay time of signal fedback to a laser cavity drastically affect the behavior of any laser. In the present case, we have noticed minor effect of delay time on output from both lasers, see figure (9).

In a SCL, the active material has a highly asymmetric gain profile. This has consequences to the material refractive index, which can be related to the gain. The increase in injection current density increases the population inversion hence increases the gain which leads to a decrease of refractive index. The amount of coupling between gain and refractive index is described by the line- width enhancement factor, α, the latest influences several fundamental aspects of all SCLs, such as line-width, the chirp under current modulation, the mode stability, and the occurrence of filamentation in broad area devices. So the dynamics of SCLs is greatly influenced by the α– factor [16].

In coupled SCLs systems, an amplitude fluctuation in one laser leads to a carrier density fluctuation, and throughα, a phase fluctuation in the same laser. The change in the relative phase leads to an amplitude change in the second laser and accompanying change in its carrier density.

The perfect choice of the control parameters and the delay time can lead periodically to the death of the output from any laser under the effect of feedback. The earlier saturation of gain before building of proper population inversion can prevent the laser from emitting light output. The frequency of the same can be altered as a result of feedback. Together with the effect on refractive index hence the line width enhancement factor, various dynamics can be expected to occur from coupled face- to-face SCLs. Results obtained enforced such conclusion.

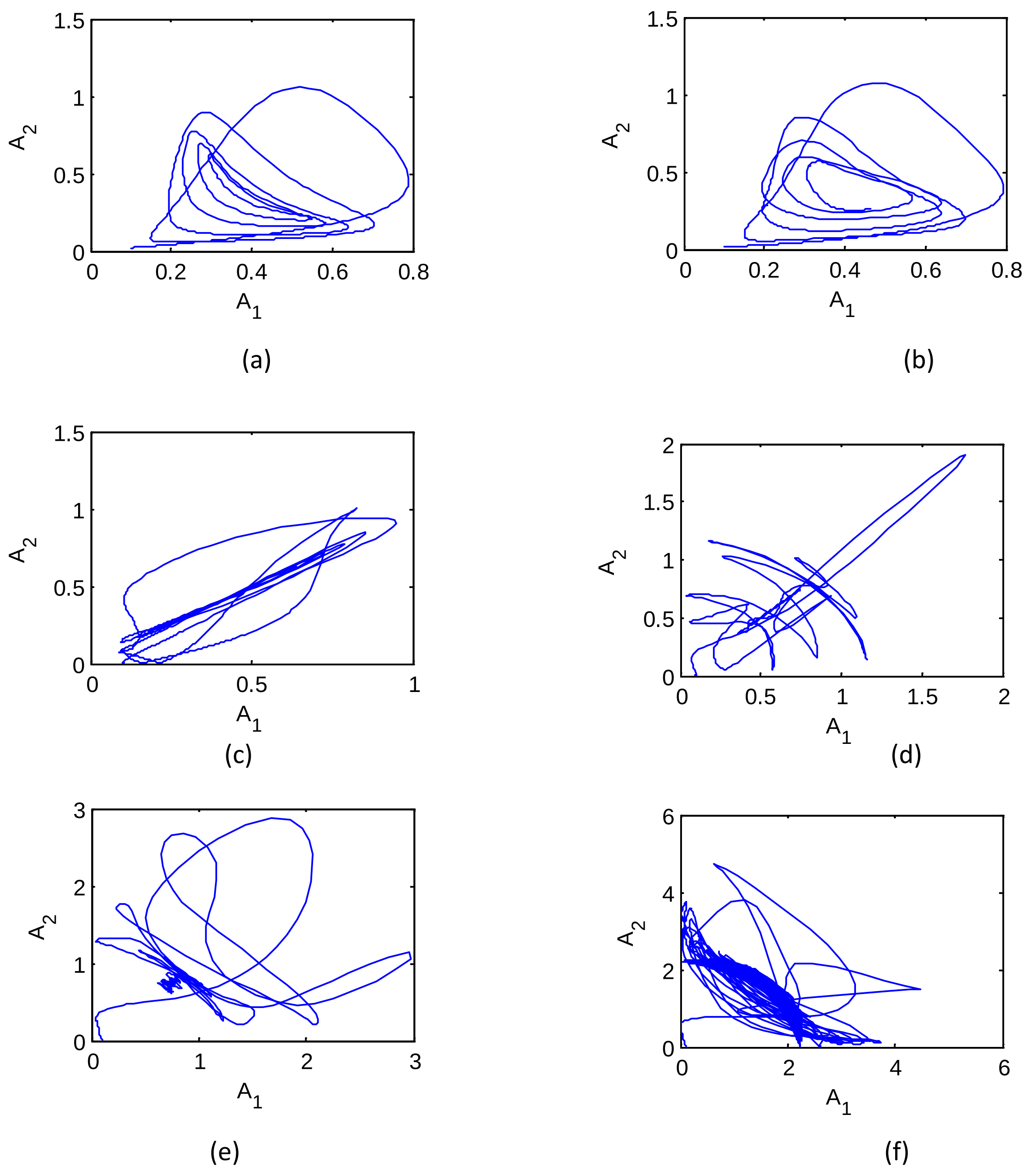


(a) (b)

(c) (d)

(e) (f)

Fig (2): Variation of field output from both lasers for $j=0.165$, $\alpha=5$, η have the values :a) 0 ,b) 0.001 ,c) 0.01 ,d) 0.1 ,e) 0.2 ,f) 0.4 .

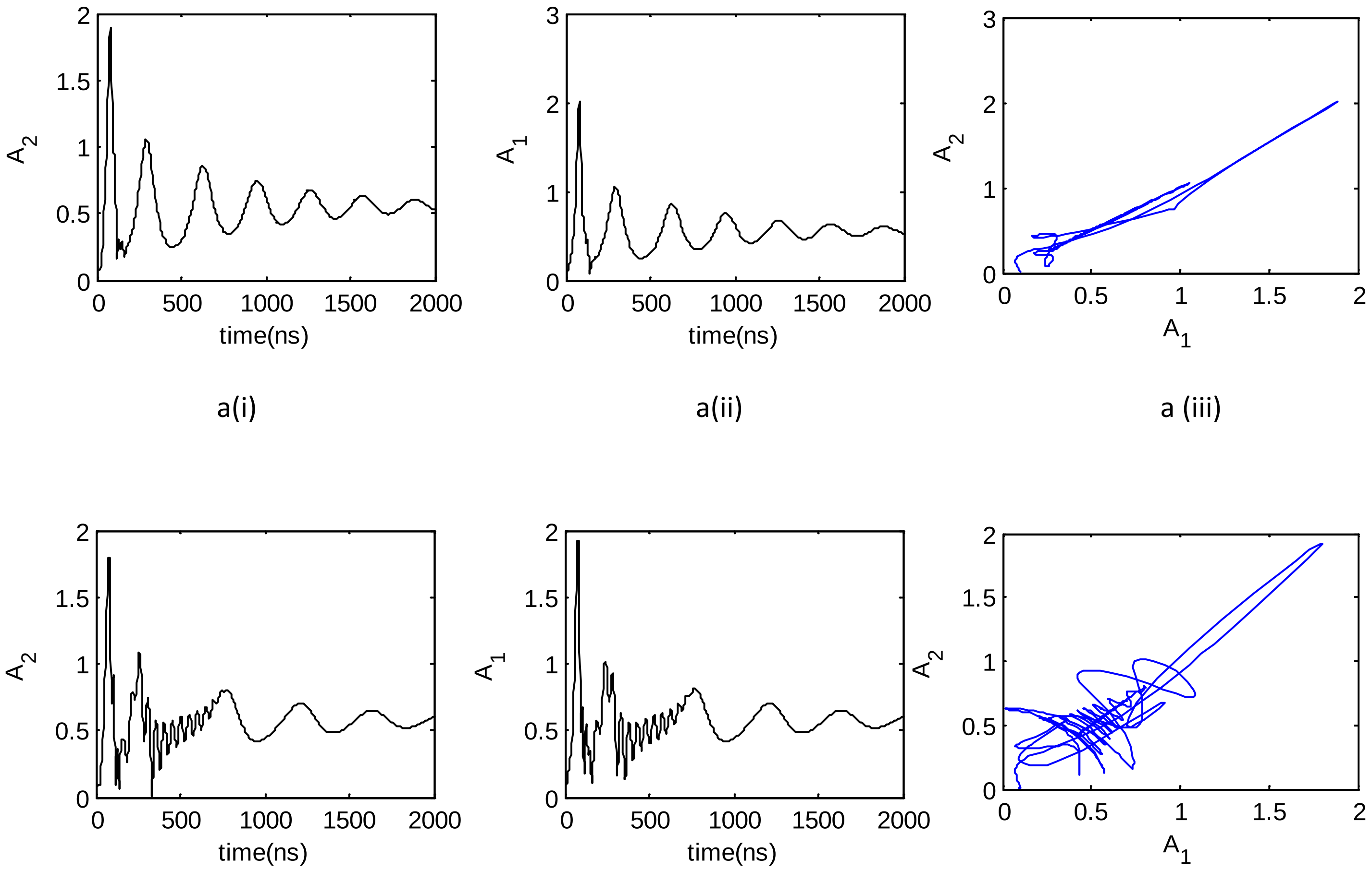


(a) (b)

(c) (d)

(e) (f)

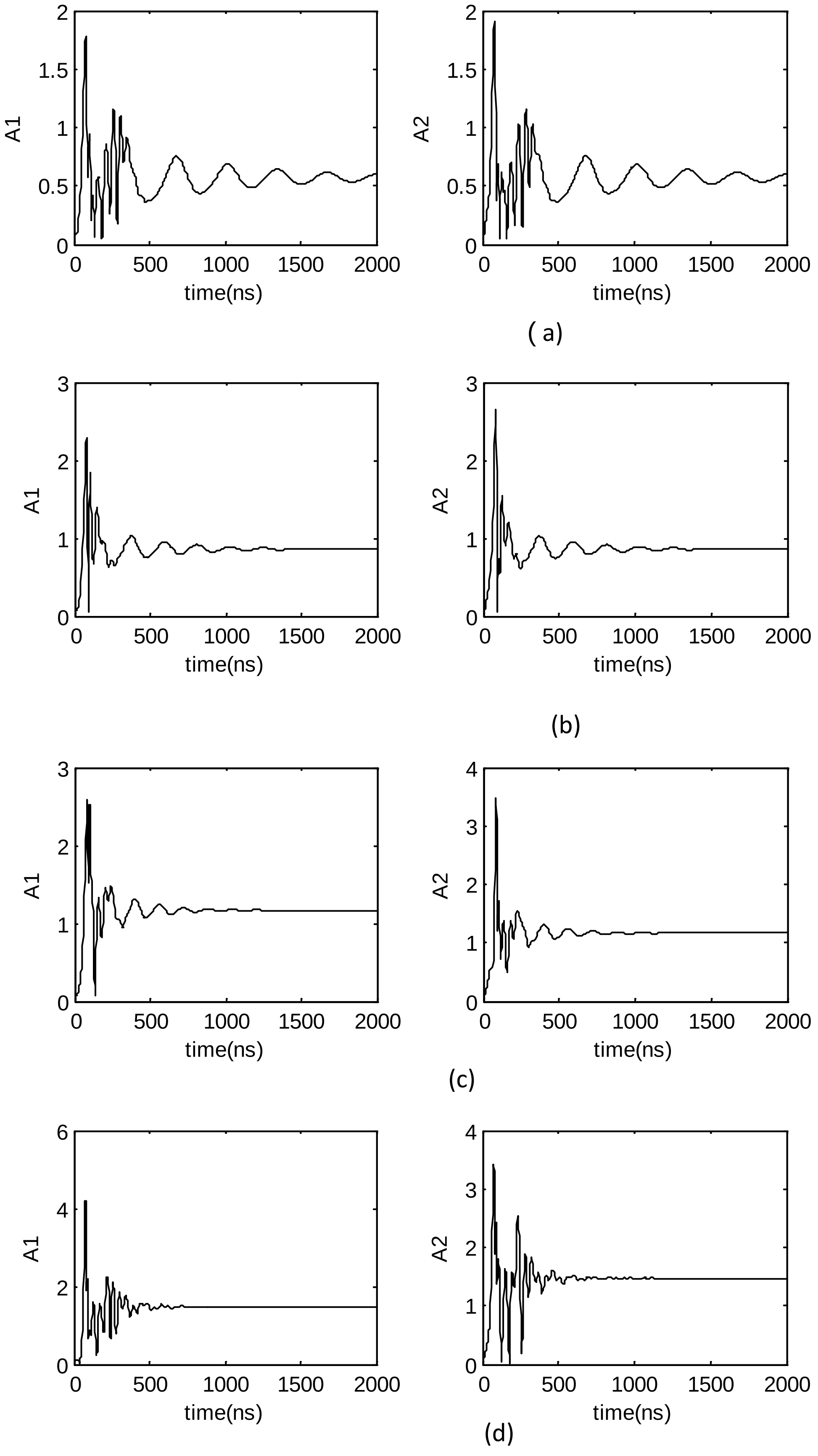
Fig(3): Attractors of the relation between A_1andA_2 for J=0.165,ω_1=ω_2=2π, T=1000,β=10^{-5},T=14,α=5, η have the values :a) 0 ,b) 0.001 ,c) 0.01 ,d) 0.1 ,e) 0.2 ,f) 0.4



a(i) a(ii) a (iii)

b(i) b(ii) b(iii)

Fig(4):a) Variation of field output from both lasers with time for a(i) a(ii) α=3.4,b(i) b(ii) α=4.5$A_1, and A_2$attracters for a (iii) α=3.4, b(iii) 4.5 and for j=0.165 and η=0.1



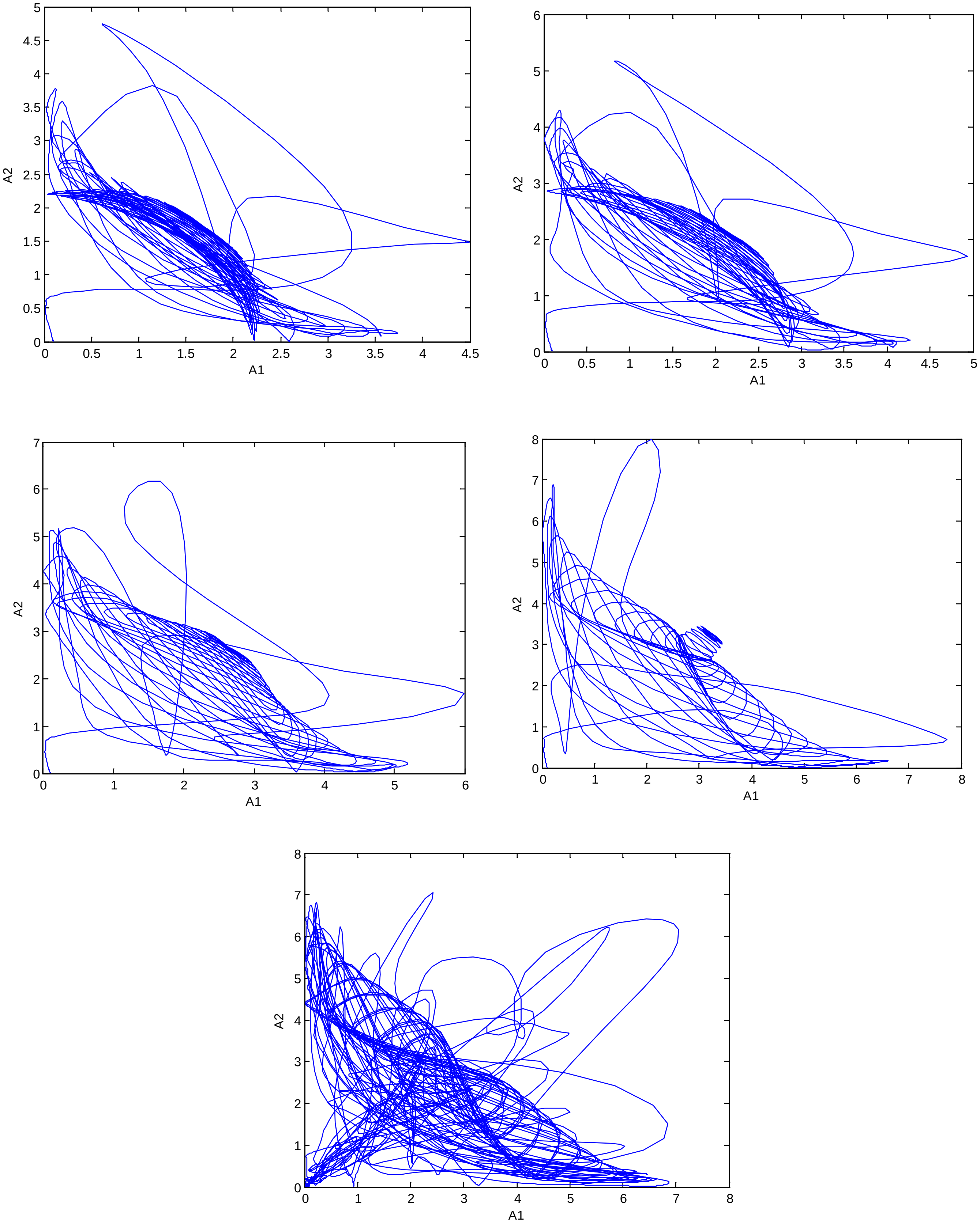
(a)

(b)

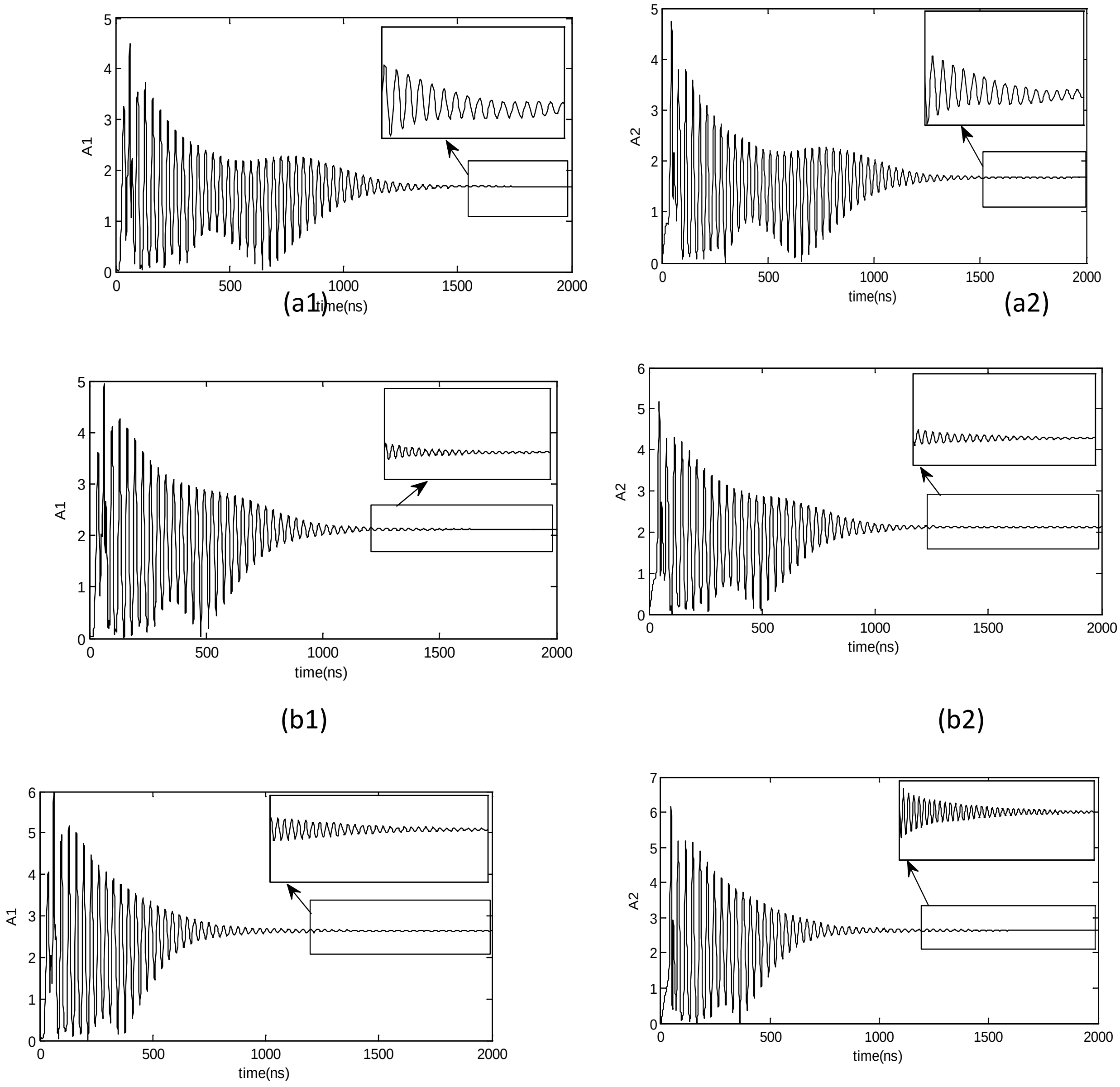
(c)

(d)

Fig(5): Variation of field output for both lasers with time for $\eta=0.1$ and for j=a) 0.165, b)0.5, c)1.0 and d)1.65



Fig(6) Attractors for the relations A_1 against A_2 for the conditions given in fig(5)



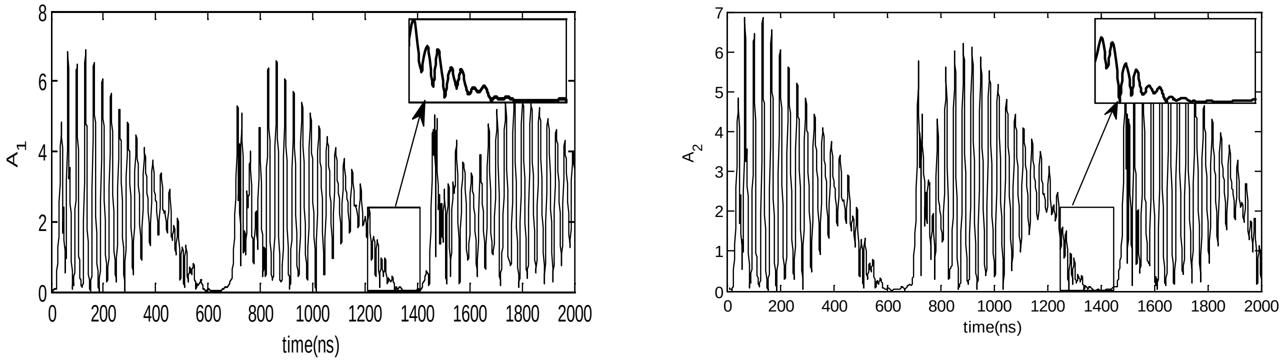
(a1) (a2)

(b1) (b2)

(c1) (c2)

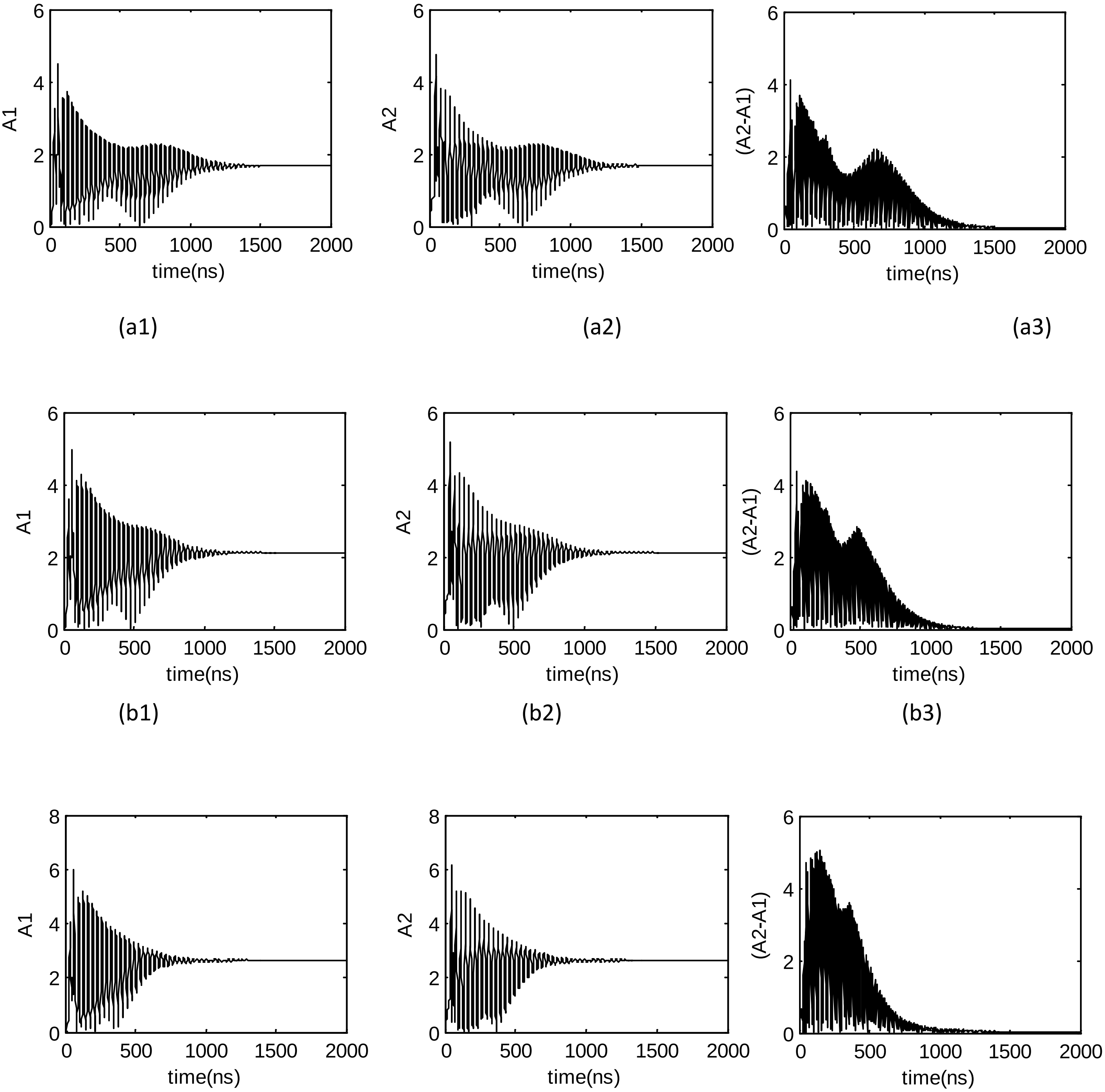
Continues

Fig(7): variation of field output from both Lasers with time for ɳ=0.4,α=5, j have the values a) 0.165 ,b) 0.5 ,c) 1.0 , d) 2.0.



d1 d2

Fig(7): Continued



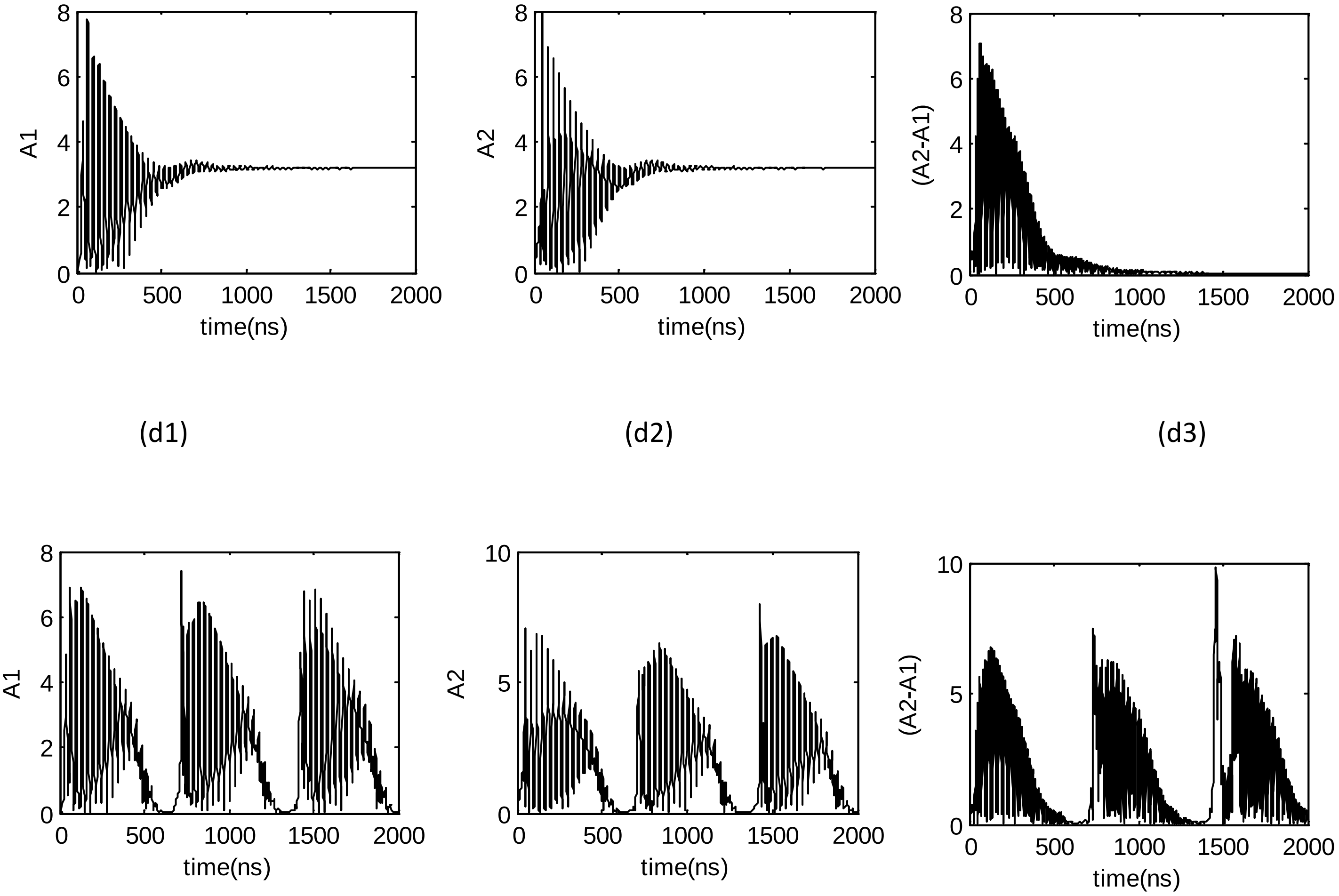
(a1) (a2) (a3)

(b1) (b2) (b3)

(c1) (c2) (c3)

Continues

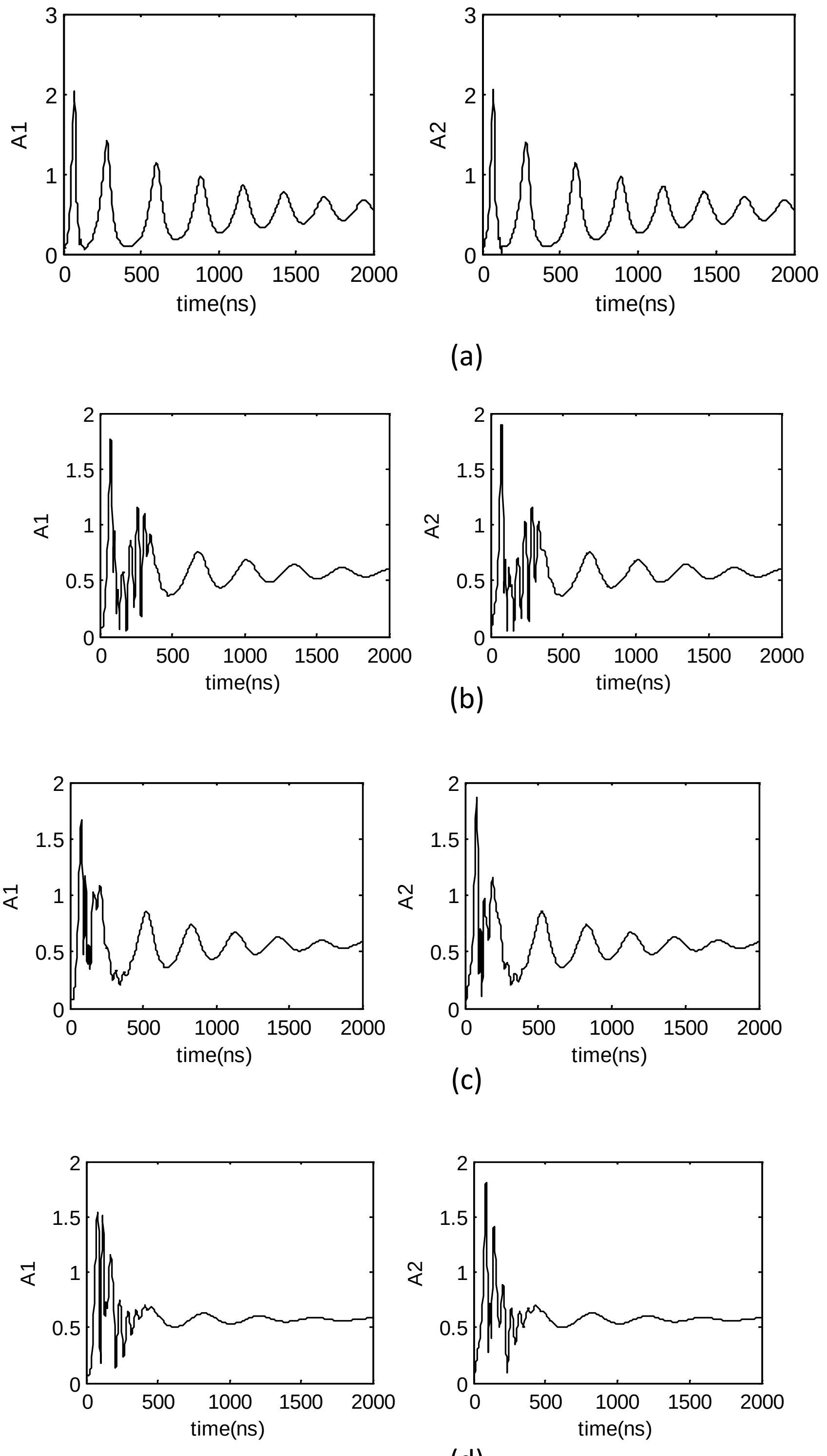
Fig (8): Variation of field output from both lasers, and (A_2-A_1) with time for α=5,ɳ=0.4 and j have the values :a)0.165,b)0.5,c)1.0,d)1.65 ,e)2.0



(d1) (d2) (d3)

(e1) (e2) (e3)

Fig (8): Continued



(a)

(b)

(c)

(d)

F(9): Variation of field output from both lasers with time for η=0.1, α=5, j=0.165, whereThave the values :a)10, b)14 ,c)16 and , d)20

conclusion:

We have studied the effect of coupling strengthbetween two synchronized face- to-face semiconductor lasers, line-width enhancement factorand the injection current densityon the dynamics of these lasers by solving the set of equations governing the field, population different and the phase of the field of each laser. The three parameters have pronounced effect on the fields, which we have studied in special, we have found that with the increase of coupling strength amplitude- death regions within chaotic fields as the injection current increased occurs.

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حركيات السعة في نظامي ليزر شبه موصل ذاتية الأقتران بوجود الضوضاء

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الخلاصة:

لقد سبرنا أغوار حركيات المجال في ليزري شبه موصل تواجه إحداهما الأخرى ومتزامنتين. تمت الدراسة تحت تأثير شدة الأقتران بين النظامين ومعامل تعزيز عرض الخط وكثافة تيار الحقن. كافة هذه المعاملات أثر في حركيات المجال المعتمدة على الزمن. ظهرت مديات إندثرت فيها سعة المجال وهي محصورة ضمن مديات فوضوية بتأثير زيادة كثافة تيار الحقن وشدة الأقتران.