Journal of Applied Physics & Nanotechnology

Review Article

Optical Injection Locking in Quantum Dot Light Emitting Diode

This article was published in the following Scient Open Access Journal:
Journal of Applied Physics & Nanotechnology
Received March 13, 2018; **Accepted** March 23, 2018; **Published** April 03, 2018

Hussein B. Al Husseini[1,2]* and Hussein A. Al Rekabie[1]

[1]*Department of Physics, College of Science, University of Thi-Qar, Nassiriya, Iraq*
[2]*Nassiriya Nanotechnology Research Laboratory (NNRL), Science College, University of Thi-Qar, Nassiriya, Iraq*

Abstract

In this work we study a Quantum Dot Light Emitting Diode (QD-LED) subject to optical injection which induces instability in slave system. Frequency detuning, bias current and the optical injection ratio were studied. Results indicate chaotic behavior via time series, attractor and bifurcation diagram. Phase-locking state is observed when both the master and slave systems work at the same frequency $\Delta\omega = 0$. We also show two cases, damping with disappearance and increasing the output signal capacity by increasing the optical injection ratio. Injection-locking and stability states were also observed.

Keywords: QD-LED, Optical injection, Instability, Chaotic bifurcation, Control

Introduction

A broad modulation bandwidth is requirement in a wide range of optical communication applications, as well as others needs narrowband frequency. Increasing the bandwidth in the direct modulation has been used but, the injection locking is shown to do best for the above mentioned requirements [1].

Semiconductor Lasers (SLs) exhibit a rich variety of nonlinearities as previous research indicated under optical injection [2], where the SL dynamics was described by the frequency of the optical injected signal add to the slave laser itself. Their difference as known detuning controls the slave system while staying the master one without affecting.

There are many applications depending on the nonlinearity and the bandwidth controlling of the system. Where, excitability can be observed in the behavior of a stable dynamical system that pulses exhibit by adding perturbation above threshold as optical injection [3]. Chaos can be seen in the behavior of these nonlinear systems [4].

The outstanding performance of the self-assembled Quantum-Dot (QD) material makes it extremely attractive for the use as optical communication systems. It has reduced temperature and independent current threshold and suitable emission in fiber-optic windows [3,5-7]. A little works deal with optical injection in QDs. One of them deals with carrier dynamics in their states [8]. The study of the dynamics in different QD states is important to know the physical parameters which control them.

Injection-locking is a very useful tool for stabilizing the semiconductor devices, however injection-locked SLs shows a rich variety of dynamics [9]. Here we used QD-LED instead of the QD lasers, because of the broad mission of QD-LED represents a challenge for researchers to control multi-mode output and to meet the requirement of injection-locking.

In this work and for optical injection locking, two QD-LED are used with almost the same frequencies, see figure 1 and the frequency detuning between them $\Delta\omega$. Light emitted from the master is injected into the slave system. When the injection locking conditions are satisfied, the frequency of the slave is locked to that of the master. There are two important parameters in injection locking: frequency detuning, $\Delta\omega$, which is the frequency difference between the master and the free-running slave system, and optical injection ratio, r_{inj}, which is a ratio between the injected power from the master and the power of the free-running slave system. The nonlinear differential equation system can be used to model the dynamics of the QD-LED [6]. The study of this system allows theoretical consideration of the properties of QD-LED, analysis of the crossover, and control. In this work an injection is applied from the 3D model of QD-LED [4].

This work studies of injection locking dynamics in QD-LED. Sec. II, states the rate

***Corresponding Author:** Hussein B. Al Husseini, Department of Physics, College of Science, University of Thi-Qar, Nassiriya, Iraq, Email: Vgfedotov47@inbox.ru

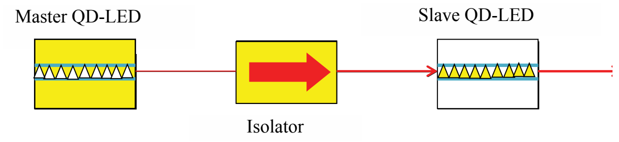

Figure 1: Optical injection system used in QD-LED optically injected.

equations model used for QD-LED dynamics. Sec. III includes the calculated results of optical injection locking with frequency detuning, bias current and ratio of the optical injection in QD-LED slave system. And conclusion in Sec IV.

QD-Led Model with Optical Injection

The external injection effect is added to the equation of the complex field and the field equation is written in the following figure [6].

$$\frac{dE(t)_s}{dt} = -\frac{1}{2}(1+i\alpha)Wn_{QD}E(t)_s - \frac{\gamma_s}{2}E(t)_s + E_{sp}(t) + \frac{k_{inj}}{\tau_{in}}E(t)_m e^{-i\Delta\omega t} \quad (1)$$

Where E_S and E_m are the complex electric fields of the slave and master system, respectively. For the slave LED with QD active region the other parameters are K_{inj} is the injection coefficient, $\Delta\omega = 2\pi\Delta\nu = \omega_m - \omega_s$ is the detuning between the master and slave systems, ω_m and ω_s, for the master and slave QD-LEDs, respectively,. The extra term has a delay time τ and the complex field is described by a delay differential equation and this is the origin of the instability of chaotic dynamics in QD-LED [4] and the Einstein coefficient W is given by $W = \{(|\mu|^2\sqrt{\varepsilon_{bg}})/(3\pi\varepsilon_o\hbar)\}/(w/c)^3$. Where ε_{bg} is the static relative permittivity of background medium ε_o is the vacuum permittivity,c is speed of light in vacuum, and μ is the dipole moment of QDs, Planck's constant ħ, and the frequency ω. The equation is known as the Lang-Kobayashi equation after their derivation. Population distributions in both WL and QD are taken into account explicitly in order to determine the correct relation between absorption and spontaneous emission spectra. $E_{sp}(t)$ is the stochastic function corresponding to the zero-mean random field for spontaneous emissions. The field has the relation of $\langle E_{sp}(t)E^*(t)\rangle = R_{sp}/2$ [4]. In this equation the asterisk (*) denotes the complex conjugate. The term R_{sp} is usually used for the effect of spontaneous emission in the photon number equation and is given by [10]

$$R_{sp} = W\,n_{QD}^2 \quad \text{..... (2)}$$

In the QD-LED system the electrons are first injection into wetting layer (WL) before they are captured by the quantum dots (QDs). The system equations describe the dynamic of the number ...ier in the QD ground state n_{QD}, the number of carrier in WL n_{wl}, and after the our transformation to Eq.(1) for the number of ph...n in the optical mode S, and the phase of the electric field φ_t which is the time dependent phase in the presence of optical feedback plays an important role, since the phase couples with the other variables. And the four equations for the number of electrons in the QDs (n_{QD}) and in the WL (n_{wl}) read:

$$\frac{ds_s}{dt} = wn_{QD}^2 - sw\,n_{QD} - \gamma_s s + \frac{k_{inj}}{\tau_{in}}\sqrt{s_m s_s}\cos\psi_t$$

$$\frac{d\varphi_s}{dt} = \frac{1}{2}\alpha wn_{QD} - \frac{k_{inj}}{\tau_{in}}\sqrt{s_m/s_s}\sin(\psi_t - \Delta\omega)$$

$$\frac{dn_{QD_s}}{dt} = \gamma_c n_{wl}\left(1-\frac{n_{QD}}{2N_d}\right) - \gamma_{rQD} - \left(wn_{QD}^2 - wn_{QD}s\right)$$

$$\frac{dn_{wl_s}}{dt} = \frac{I}{e} - \gamma_{rwl} - \gamma_c n_{wl}\left(1-\frac{n_{QD}}{2N_d}\right) \quad (3)$$

We introduce a phase $\psi_t = \varphi_s(t) - \varphi_m(t) - \Delta\omega$, here, the induced processes of spontaneous emission and reabsorption in the QDs are modeled by the first and second terms of the first equation of the system Eqs. (3) [10]. γ_{rQD} and γ_{rwl} are the non-raditive decay ...es of the number of carriers in the QD and WL resp...tively, N_d is the number of QDs ,and I is the injection current , e is the elementary charge γ_c is the capture rate from WL into the dot, γ_s is the output coupling rate of photons in the optical mode. The main goal of this work is to provide a model reproducing qualitatively the experimental results and showing the chaotic spiking of QD-LED. To do so, we rescale the system Eqs(3) to a set of dimensionless equations. Defining a new variables and dimensionless parameters by the following,

X=S , $y = \frac{W}{\gamma s}n_{QD}$, Z= $\frac{n_{wl}\gamma_s}{W}$

$\gamma = \frac{\gamma_s}{\gamma_{rwl}}$, $\gamma_1 = \frac{W}{\gamma_s}$, $\gamma_2 = \frac{W}{\gamma_{rwl}}$, $\gamma_3 = \frac{\gamma_{rQD}}{\gamma_{rwl}}$, $\gamma_4 = \frac{\gamma_c}{r_{wl}}$,

$N_d \equiv a$ and $\delta_\circ = \frac{I}{We}$, and the time scale $\acute{t} = \gamma_{rwl}t$. The system Eqs(3) can be rewritten in the following ;

$$\dot{x} = \gamma\left(\left(\frac{y^2}{\gamma_1}\right) - x(y+1) + 2q\sqrt{x_m x_s}\ \cos(\psi_t)\right)$$

$$\dot{\emptyset} = \frac{1}{2}\alpha\gamma y - q\sqrt{\frac{x_m}{x_s}}\sin(\psi_t - \Delta\omega)$$

$$\dot{y} = \gamma_2 z\left(\gamma_1 - \frac{y}{2a}\right) - y(\gamma_3 + \gamma y) + \gamma_2 xy$$

$$\dot{z} = \gamma_4\left(\delta_\circ - z + \frac{yz}{2\gamma_1 a}\right) - z \quad (4)$$

$$\psi_t = \varphi_t - \Delta\omega t$$

Here the upper subscript "dot" (·) refers to differentiation with respect to ($\acute{t}$). The bias current is representing by ($\delta_\circ$). Where $\acute{\tau} = \gamma_{rwl}\tau$ and $\eta_{inj} = \frac{K_{inj}}{\gamma_{rwl}\tau_{in}}$. Then, four coupled equations are essential for QDLED with optical injection and they show unstable oscillations and chaotic dynamics in their output powers like three coupled equations in Lorenz systems. We discuss the dynamics of chaos in QD-LED without external effect and show various routes to chaos under parameter variations. The system rate equations (4) are solved numerically using the fourth-order Runge-Kutta method by Matlab system. The parameters used in simulation are: γ =0.158, γ_1 = 0.049, γ_2 = 0.026, γ_3 = 0.03, γ_4 =0.078, and a = 0.891. The initial values are: x_o = 0.066, $Ø_o$ = 0.066, y_o = 0.99, z_o = 0.0049. They are obtained by solving the system (4) at steady state.

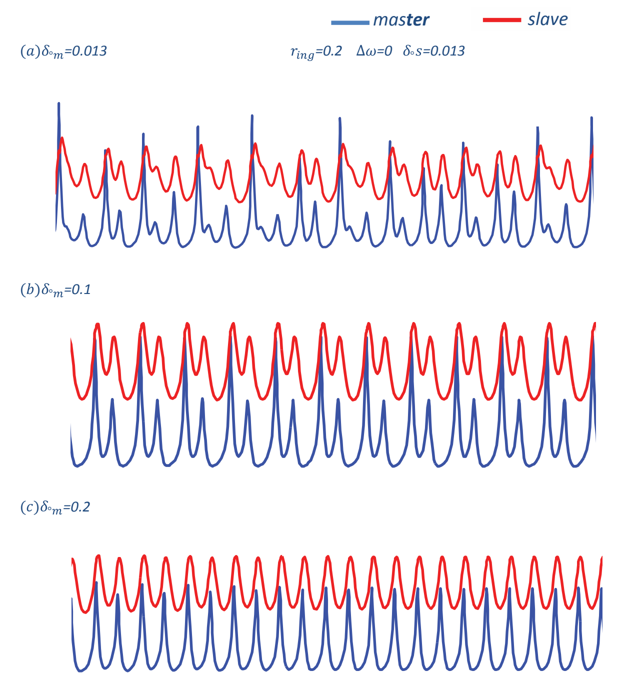

Figure 2: phase locking calculated for the QD-LED model under the condition of bias current changing and $\Delta\omega=0$, $\delta_{os}=0.013$ and $r_{inj}=0{,}2$: (a) $\delta_{os}=0.013$, (b) $\delta_{os}=0.1$ and (c) $\delta_{os}=0.2$.

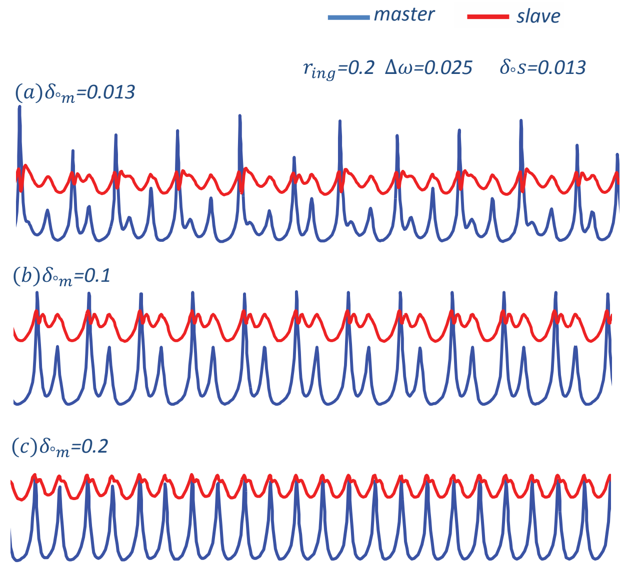

Figure 3: phase locking calculated for the QD-LED model under the condition of bias current changing and $\Delta\omega=0.025$, $\delta_{os}=0.013$ and $r_{inj}=0{,}2$: (a) $\delta_{os}=0.013$, (b) $\delta_{os}=0.1$ and (c) $\delta_{os}=0.2$.

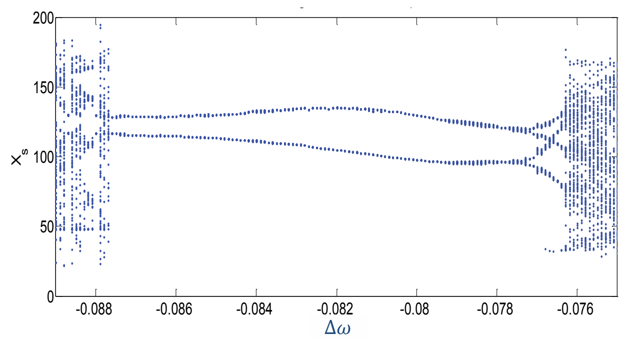

Figure 4: Bifurcation diagram of output photon dependence of detuning when (δom= 0.1) to master and (δos = 0.013) to slave, and injection ratio (rinj= 0.2).

Effect of Optical External Injection

When studying the effect on external optical injection of QD-LED for both the master and the slave systems, and as expected, when they work at the same frequency, i.e., $\Delta\omega=0$, one do not obtain a change in the dynamic phenomenon of both the systems as seen in figure 2(a), but there is a large increase in effort compared to the increase of optical external injection r_{inj} and master bias current δ_{om} at a small value of the bias current for slave ($\delta_{os}=0.013$) as seen later.

We will now briefly present examines of bias current effect upon to QD-LED dynamics in both of master and slave systems. In figure 2(b) and in the case of bias current ($\delta_{om}=0.1$) of the master which its corresponding to the periodic state and bias current ($\delta_{o}=0.013$) of the slave which its corresponding to the chaotic state, the behavior of slave move to of the double period and when taking the bias current ($\delta_{o}=0.2$) and ($\delta_{o}=0.3$ which is not drawn) for the master, the slave be the movements of periodic as seen in figure 2 (c). In order to fully demonstrate the frequency detuning effect, a small value is chosen for the difference between the slave and the master frequencies as seen in figure 3, figure 3(a) shows calculating the effect at the value of 0.013 for the bias current, we observe two things. First, a decrease in the signal capacity, and second, the breadth of the signal width without a phase matches. Similar results are obtained when calculating the frequency effect at values 0.1 and 0.2 of the bias current as in figures. 3 (b) and (c), respectively. When we compare the two results above, we observe the phase-locking status when they work at the same frequency of the slave and the master, but at a small frequency difference between them we notice the phase spacing and decrease in amplitude.

And contrary to the above of the bias current value between master and slave, one did not have a mutual effect and a result will only be chaos for slave.

From above cases, can be said that the increase of the master's contribution to the slave is more effective at frequency detuning ($\Delta\omega=0$) than the increasing at frequency detuning ($\Delta\omega=0.025$) which forces the behavior of the slave to take the same behavior as the movements of the master.

Now we present effect of frequencies by scanning wide range of the frequency detuning between the master and slave systems as seen in figure 4. When the bias current is proved to the master ($\delta_{o}= 0.1$) and the slave ($\delta_{o} = 0.013$), the dynamic behavior at the injection ($r_{inj}= 0.2$)which is present as bifurcation scenario diagram motions from the chaos at ($\Delta\omega=-0.09$) then follows a period doubling (two cyclic) with frequency detuning from ($\Delta\omega= -0.0875$) to ($\Delta\omega= -0.0775$) then it will be 4 cyclic and when the detuning frequency increases over ($\Delta\omega= -0.076$) the behavior to be of the motility disorder (chaotic state).

Figure 5(a) shows a new technique of time series appearing several dynamics with different values of detuning, the effect of detuning on the photon output where it becomes (Δω=-0.082, -0.0772 and -0.076), which represent the period doubling, four period and chaotic, respectively. And at all these detuning the locking is observed. Figure 5(b) shows the attractors plotting (x-y phase portraits) of the QD-LED slave system for the same values under discussion in figure 5(a) of the detuning. All figures 5(a and b) corresponding to figure 4 and the relation between the photon output and detuning with fixed both the injection current and a ratio of optical injection, It is known as bifurcation scenario .

Finally, in figure 6, we consider an examine of photon output with optical injection ratio. Figure 6 shows different dynamics, and a development in the behavior of the photon from the chaos state, which ends in the value 0.02 of optical injection ratio and then get damping of the signal directly and continue until the value 0.05 of optical injection ratio followed by the case of semi-periodic and later moving upward for the output capacity and continue in the doubling period state.

As we refer in figure 6 above, is shown several dynamics to QDLED slave at high current compare with (δ_o=0.013) to the master and small detuning frequency at (Δω=0.025) and the other parameters as in Sec II. For illustration we must mention the behavior of QD-LED here is completely different from the behavior of the QD laser under the effect of optical injection, where we have two cases, the first is the damping and disappearance of the slave signal at the value of 0.02 and it is a unique case of the QD-LED behavior, which penetrated us in previous work when studying the filtered optical feedback [6]. And the second case,

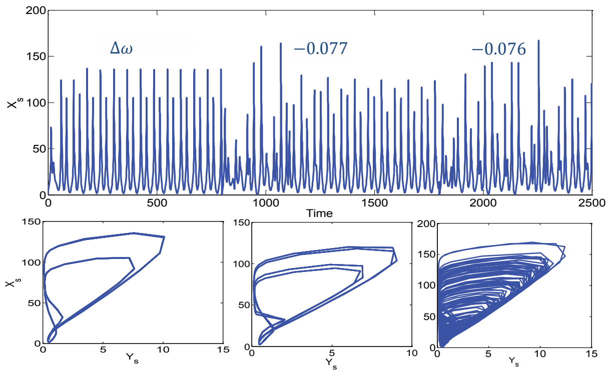

Figure 5: Examples of output photon dynamics for QD-LED slave by using detuning effect. (a) Time series. (b) Attractor, corresponds to bifurcation in figure 4.

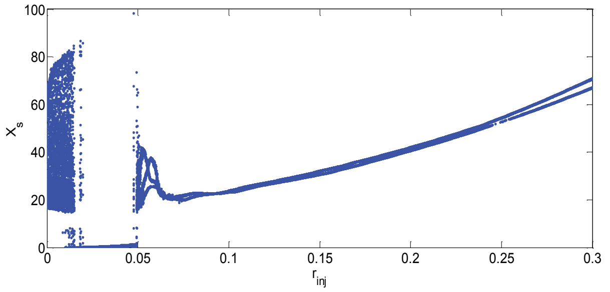

Figure 6: Bifurcation diagram of output photon dependence of optical injection ratio when (δ_o= 0.1) to master and (δ_o = 0.013) to slave, and detuning (Δω= 0.025).

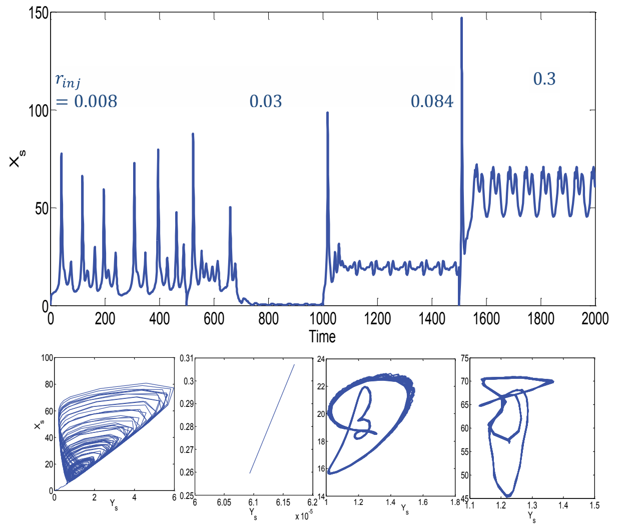

Figure 7: Examples of output photon dynamics for QD-LED slave by using optical injection ratio effect. (a) Time series. (b) Attractor, corresponds to bifurcation in figure 6.

increase the output capacity of the slave by increasing the effect of optical injection, which is also a result obtaining for the first time.

We can be illustrated the above figure by the time series and the corresponding attractor plotting. figure 7(a) shows a clear variation of the photon output behavior for cases which it is passes by the effect of changing the optical injection ratio. It should be noted that all these cases get as result the effect of the field strength and the amount of perturbation affecting on the dynamics of the slave. The corresponding attractor shows each case and we note that the corresponding attractor of the signal damping state is a line up and a homoclinic attractor with large capacity for corresponding value 0.3 as seen in figure 7(b).

Conclusion

To organize conclusion studying the effect on external optical injection of QD-LED for both the master and the slave systems, First, bias current effect upon to QD-LED dynamics is examined, we observed the phase-locking status when they work at the same frequency of the slave and the master, but at a small frequency difference between them we notice the phase spacing and decrease in amplitude. Second, effect of frequencies by scanning wide range of the frequency detuning between the master and slave systems is presented, results show the period doubling, four period and chaotic, respectively. Finally, optical injection ratio is examined, different dynamics are shown, and at 0.02 of optical injection ratio get damping of the signal and later moving upward for the output capacity and continue in the doubling period state. Injection-locking and stability states are observed.

References

1. Lau EK, Sung HK, Wu MC. Frequency response enhancement of optical injection-locked lasers. *IEEE Quantum Electron*. 2008;44:90-99.
2. Thevenaz L, Floch SL, Alasia D, et al. Novel schemes for optical signal generation using laser injection locking with application to Brillouin sensing. *Meas Sci Technol*. 2004;15(8):1519-1524.
3. Vainio M. Diode Lasers with optical feedback and optical injection. *Helsinki*

University of Technology. 2006.

4. Al Husseini H, Al Khursan A, Al Naimee K, et al. Modulation Response, Mixed mode oscillations and chaotic spiking in Quantum Dot Light Emitting Diode. *ELSEVIER. Chaos. Solitons & Fractals. Nonlinear Science. Nonequilibrium and Complex Phenomena*. 2015;78:229-237.
5. Kais Al Naimee, Hussein Al Husseini, Amin Al Khursan. Complex dynamics in Quantum Dot Light Emitting Diodes. *Eur Phys J D*. 2015;69:257.
6. Hussein B. Al Husseini, Kais A. Al Naimee, Amin H. Al-Khursan, et al. External modes in quantum dot light emitting diode with filtered optical feedback. *Journal of Applied Physics.* 2016;119(22):224-301.
7. Amin H Al-Khursan, Khakani MK Al, Mossawi KH Al, Third-order non-linear susceptibility in a three-level QD system. *Photonics and Nanostructures-Fundamentals and Applications.* 2009;7(3):153–160.
8. Pausch J, Otto C, Tylaite E, et al. Optically injected quantum dot lasers: impact of nonlinear carrier lifetimes on frequency-locking dynamics. *New Journal of Physics*. 2012;14(5):053018.
9. Erneux T, Viktorov EA, Kelleher B, et al. Optically injected quantum-dot lasers. *Optics Letters*. 2010;35(7):937-939.
10. Gardiner W. Handbook of Stochastic Methods. *Springer Berlin Heidelberg.* New York. 1985.

Copyright: © 2018 Hussein B. Al Husseini, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.