

Mechanism of interaction between electromagnetic fields and living organisms

Fritz-Albert Popp¹ & ZHANG Jinzhu (CHANG Jiin-Ju, 张锦珠)^{1,2}

1. International Institute of Biophysics ev., IIB D-41472 Neuss, Germany (email: ao221@uni-koeln-de);

2. Institute of Biophysics, Chinese Academy of Sciences, Beijing 100101, China (email: Changjj@sun5.ibp.ac.cn)

Received February 17, 2000

Abstract Based on nonlinear phenomena of biophoton emission observed in the past, an interference model concerning with the mechanism of interaction between living organisms and electromagnetic fields was raised. Caused by biological nonlinearly polarizable double layer, destructive interference of incoming and reflected waves establishes in the outside. As a consequence, in the inside constructive interference takes place at the same time. The interference patterns may play an important role in biological self organization and in biological functions. We investigate the boundary conditions necessary for explaining these non-linear optical effects in terms of the phase conjugation. It turns out that there are solutions of the Maxwell equations which satisfy destructive interference of biophotons in agreement with the experimental results. Necessary provisions are nonlinearly polarizable optically active double layers of distances which are small compared to the wavelength of light. In addition, they have to be able to move into the nodal planes of the impinging waves within a small time interval compared to the coherence time. These conditions are likely fulfilled in the optically dense, but ordered and optically excited, highly polarizable living matter.

Keywords: electromagnetic fields, interaction mechanism, biophotons, coherence, interference.

Biophoton emission from biological living systems is now a well established and accepted universal phenomenon. The intensity ranges from a few up to some hundreds of photons $\cdot s^{-1} \cdot cm^{-2}$ of surface area of the tissue, and the spectrum covers from 260 nm to 800 nm. The photocount statistics displays a Poissonian distribution, and the “delayed luminescence” which is the relaxation function of biophoton emission after excitation of the living system by external light follows a hyperbolic characteristic. These are necessary and sufficient conditions for the coherence of the biophoton field. However, up to now investigations of biophotons have revealed a variety of results which are not explainable in terms of ordinary biochemistry or linear biophysics. Some typical examples are given in the following:

Popp and Chang et al.^[1,2] have shown that bioluminescence of *dinoflagellates* displays synchronous flickering of light emission as shown in fig. 1.

Schamhart et al. and Scholz et al.^[3, 4] found that the intensity of “delayed luminescence” of tumor cells increased in a nonlinear way with increasing cell density, while that of normal cells, after having arrived at a definite cell mass, decreased with increasing cell density as shown in fig.

2.

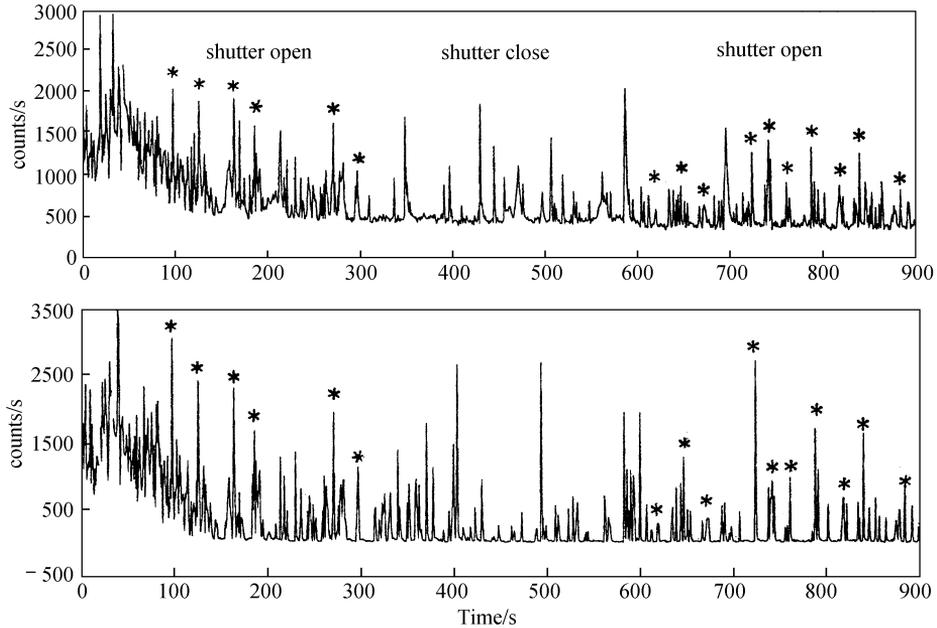


Fig. 1. Synchronous flickering of *dinoflagellates*. Two cultures of *dinoflagellates* were placed separately in chamber A (upper) and Chamber B (lower). By closing the shutter between them from 300 s to 600 s, their bioluminescence flickering was unsynchronous. When they were in light contact by opening the shutter, their flickering was synchronous. The stars indicate the synchronous flashes.

Galle et al.^[5] reported that female *daphnia* in the same development stage did not display linearly increasing biophoton emission with increasing number, rather an interference-like pattern which showed maxima and minima of biophoton intensity at definite average distances between *daphnia* (fig. 3).

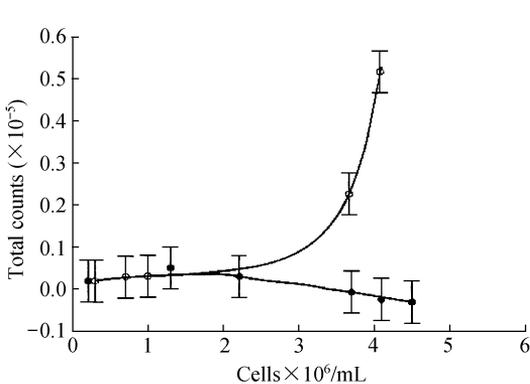


Fig. 2. Delayed luminescence of tumor cells and normal cells. With increasing cell density the delayed luminescence of tumor cells increases nonlinearly (upper curve), while that of normal cells decreases (lower curve).

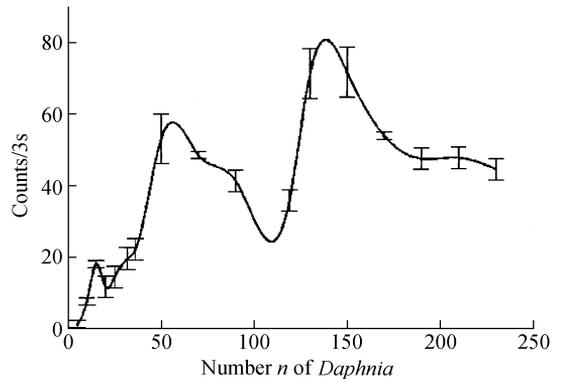


Fig. 3. Interference-like biophoton emission from *Daphnia* in water. *Daphnia* displays nonlinear biophoton emission with increasing density. The minima and maxima can be assigned to definite mean values of their mutual distances in the population.

Vogel et al.^[6] showed that bacteria absorb light from media in a way that at a definite density of bacteria the absorbance was the highest and might decrease with increasing number of bacteria (fig. 4).

Belousov et al.^[7] reported that sub-additive relationships of photon emission from the shell and the interior of eggs were dependent on the development stage of the chicken embryos.

This paper concerns a possible mechanism behind these nonlinear interactions between living systems and weak photon emission. The mechanism can also be applied to explain the interaction between living organisms and weak electromagnetic fields.

1 Basic considerations

The basic idea understanding all these phenomena is the superposition of electromagnetic

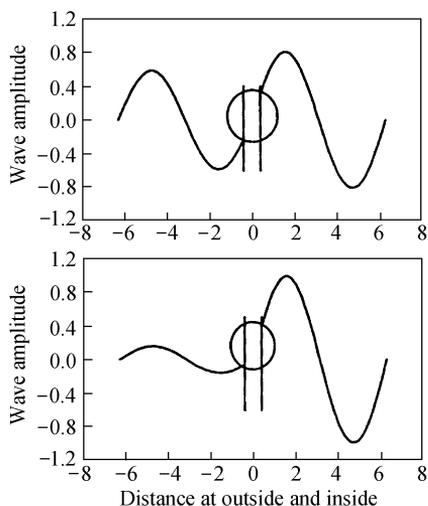


Fig. 5. Principle of destructive interference during absorption. The idea of this paper is that destructive interference of incoming and reflected waves establishes in the outside caused by a biological nonlinearly polarizable double layer. As a consequence, in the inside constructive interference takes place.

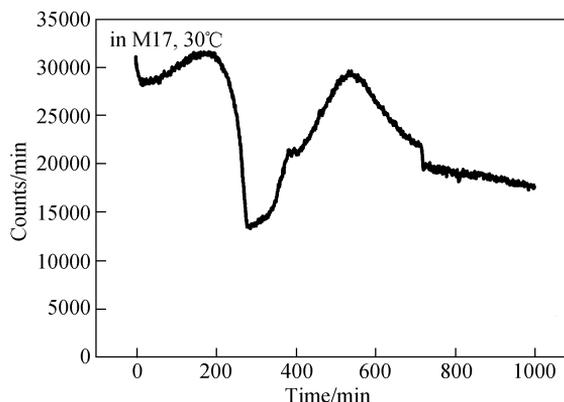


Fig. 4. Anomalous absorption of photons by bacteria in culture medium. Growing bacteria in culture medium absorb light from the permanently emitting medium in definite densities.

fields, in particular biophotons, in a way that during biologically relevant time intervals within biologically relevant structures, interference patterns of destructive and constructive interference are built up that “organize” the movement and activity of the biomolecules within and between the cells (fig. 5).

In order to explain this idea we take a cell as a simple example. As is well known, an optically allowed transition of a molecule within a cell has a typical transition time of some nanoseconds. This decay time is also the coherence time, since within this time interval no breakdown of the phase relations takes place in the travelling wave packet. After this time interval the light may have passed already a distance of about 10 cm which is large compared to the size of a cell. This means that the picture of localized photons within cells does not reflect the truth. Rather, a molecule in the optically dense matter of a cell does react to the phases of oscillatory electromagnetic fields like a boat in the sea swinging on the waves rather than absorbing locally single light quanta. Actually, absorbance and emission of photons is then a

quite non-local event based on probability distributions with a rather rare chance for a definite local event. Consequently, it is unlikely that specific molecules are responsible for biophoton emission. In addition, it is impossible that the phase relations of biophotons get lost within the domain of a cell that always provides even for chaotic light the classical coherence volume. As Dicke pointed out about 40 years ago^[8], it is even wrong to suggest that a photon field is completely chaotic as soon as the density of the matter under consideration is high compared to the reciprocal of the coherence volume of the photon field under consideration, or, in other words, as soon as the wavelength is large compared with the mean distance of the possible absorbers. The Dicke model predicts the significance of interference patterns within the volume under investigation. The Dicke condition is obviously fulfilled in the case of living matter where, for instance, the distance between neighbored base pairs of DNA is some Angstrom compared to about 500 nm of the wavelength of the light. From the classical point of view and even more accurately from the quantum description, the Dicke theory forces us to take account of a significantly high degree of coherence of biophotons within living matter. We therefore have reasons to assume that the photons within a cell culminate up to a field of almost full coherence to such an extent that it can be truthfully described in terms of eigenstates of the annihilation operator representing then a fully coherent field. The experimental evidence has been given by the following two reproducible and generally valid results of biophoton experiments in all living systems.

(1) There is almost perfect agreement between the photocount statistics of biophotons and a Poissonian distribution, for both stationary and dynamic fields, e.g. the relaxation of reemission of light from the living system after illumination with external light^[9].

(2) The hyperbolic character of the function that describes the relaxation process of “delayed luminescence” after exposure of the system to external excitation, irrespective of whether white light, monochromatic light, or other kinds of electromagnetic or mechanical energy are applied^[9–13].

In view of the coherence of the biophoton field, all of the strange results mentioned at the beginning of this paper are quite easily understandable. The explanation is then based on dynamic interference patterns of a broad banded electromagnetic field covering the optical range. It has to have a tendency of destructive interference in the extracellular space that, on the other hand, is compensated for by a corresponding overweight of constructive interference within the intracellular space. Actually, this simple hypothesis explains (i) that synchronous flickering will take place as soon as the balance of destructive interference at the outside and constructive interference within the inside is perturbed by any distortion, (ii) that tumor cells display a higher emission rate than normal ones owing to their loss of coherence, (iii) that cells or cellular systems organize their mutual distance and orientation by means of the interference pattern that is created after mutual emission and reemission of coherent biophotons, and (iv) that bacteria may absorb photons from radiating nutritional medium within the coherence volume. In the following parts we will answer why destructive interference takes place preferentially outside and constructive interferen-

ce inside the living matter.

2 Elements of theory

Optical phase conjugation involves use of any of nonlinear optical phenomena to exactly reverse the direction of propagation of a light beam. The basis of our hypothesis is that living systems are able to display phase conjugation of electromagnetic waves in such a way that they may move always into the nodal planes of the impinging electromagnetic waves so that at every space-time point the reemitted wave takes the negative amplitude of the incoming wave. Since phase conjugation suffices for the reemitted electric wave amplitude $E(\mathbf{r})_r$ to become proportional to the complex conjugate $E^*(\mathbf{r})_i$ of the incident wave, we simply have to look then for solutions of the form $E^*(\mathbf{r}) = -E(\mathbf{r})$ which means that only the imaginary (uneven) part of the field amplitude is reflected, while the real part ($E^* = -E$) penetrates the biological subject under investigation. In the present paper we show that a double layer of nonlinear polarizability may provide the necessary boundary conditions for getting destructive interference outside, and constructive interference within the subject. However, in contrast to a nonliving system, the double layer should be movable, and the whole system should use the phase information to enable the movement within a time interval that is small compared with the coherence time T into a position where at least one of the nodal planes of the electric field components of the incoming electromagnetic waves matches most efficiently the double layers of the biological system. Figs. 5 and 6 display this situation.

The classical description of this phenomenon follows the usual derivation of classical electrodynamics. One starts from the Maxwell equations (eqs. (1)—(4)).

$$\nabla \cdot \mathbf{D} = \mathbf{r}, \tag{1}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{2}$$

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}, \tag{3}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4}$$

where E , B , H and D are the electric field strength, the magnetic induction, the magnetic field strength and the displacement, respectively, r is the charge density, j the current density, t the time. By combining Ampere's and Faraday's laws and by introducing the polarization vector P ($=D - \epsilon_0 E$) in homogeneous, nonmagnetic and non-conducting material without free charges, one gets the well known wave equation

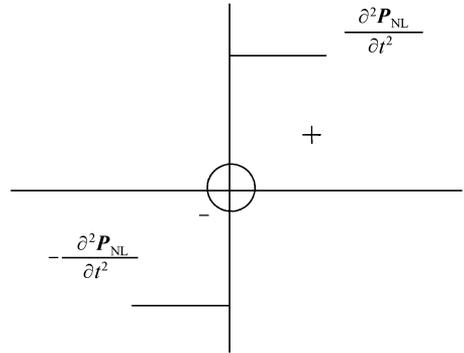


Fig. 6. Double layer of nonlinearly polarizable matter.

$$\nabla^2 \mathbf{E} - \mathbf{m}_0 \mathbf{e} \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mathbf{m}_0 \frac{\partial^2 \mathbf{P}_{\text{NL}}}{\partial t^2}, \quad (5)$$

where \mathbf{m}_0 and \mathbf{e} are the permeability and the dielectric constant of the material, respectively. The linear part of the polarization which is proportional to \mathbf{E} has been separated since only the non-linear part \mathbf{P}_{NL} which includes quadratic and higher order dependency on \mathbf{E} plays a certain role in phase conjugation. The reversal of the direction of the reflected beam into the same optical path of the incident beam as a result of phase conjugation is a consequence of eq. (5). Actually, as soon as a solution of the wave equation including non-linear polarization is known, any backward going wave is also a solution of the Maxwell equation, as its complex amplitude is everywhere the complex conjugate of the incident wave. This means that the transformation of $\mathbf{E}(\mathbf{k}, \mathbf{w})$ of the incident wave into $a\mathbf{E}^*(-\mathbf{k}, \mathbf{w})$ provides a solution of the reflected wave, with the constant a as an arbitrary complex value.

Actually, take $\mathbf{E}_1(\mathbf{r}, t) = 1/2\mathbf{J}(\mathbf{r})\exp(-i(\mathbf{w}t - k z)) + \text{c.c.}$ as a solution of eq. (5). Then after insertion into the homogeneous part of eq. (5) (which is always valid outside the matter under study) we have the condition

$$\nabla^2 \mathbf{J}(\mathbf{r}) + [\mathbf{w}^2 \mathbf{m} \mathbf{e}(\mathbf{r}) - k^2] \mathbf{J}(\mathbf{r}) + 2i k \frac{\mathbf{J}(\mathbf{r})}{z} = 0. \quad (6)$$

Now, take instead of eq. (6) the complex conjugated

$$\nabla^2 \mathbf{J}^*(\mathbf{r}) + [\mathbf{w}^2 \mathbf{m} \mathbf{e}(\mathbf{r}) - k^2] \mathbf{J}^*(\mathbf{r}) - 2i k \frac{\mathbf{J}^*(\mathbf{r})}{z} = 0, \quad (7)$$

which is just the same wave equation applied to the wave propagation in the $-z$ direction of the form

$$\mathbf{E}_2(\mathbf{r}, t) = 1/2\mathbf{I}(\mathbf{r})\exp(-i(\mathbf{w}t + k z)) + \text{c.c.}, \quad (8)$$

provided

$$\mathbf{I}(\mathbf{r}) = a\mathbf{J}^*(\mathbf{r}), \quad (9)$$

where a is any constant.

In general this does by no means lead to destructive or constructive interference, unless $a\mathbf{E}^*(-\mathbf{k}, \mathbf{w}) = -\mathbf{E}(\mathbf{k}, \mathbf{w})$ for any instant t . We will show now that this further condition may be satisfied under definite boundary conditions which are likely to be fulfilled in biological systems. At first we define an optical double layer (fig. 6) by eqs. (10a) and (10b):

$$\nabla^2 \mathbf{E} - \mathbf{m}_0 \mathbf{e} \frac{\mathcal{J}^2 \mathbf{E}}{\mathcal{J} t^2} = \mathbf{m}_0 \frac{\mathcal{J}^2 \mathbf{P}_{\text{NL}}}{\mathcal{J} t^2}, \quad z > 0, \quad (10a)$$

$$\nabla^2 \mathbf{E} - \mathbf{m}_0 \mathbf{e} \frac{\mathcal{J}^2 \mathbf{E}}{\mathcal{J} t^2} = -\mathbf{m}_0 \frac{\mathcal{J}^2 \mathbf{P}_{\text{NL}}}{\mathcal{J} t^2}, \quad z < 0. \quad (10b)$$

For the penetrating wave \mathbf{E} ($z > 0$) the second time-derivative of nonlinear polarization shall be just opposite to that of the reflected wave \mathbf{E} ($z < 0$). It is clear that this can be realized by double layers

like the cell membranes or the exciplexes (excited complexes) of the DNA^[9]. Biological systems are the most suitable candidates for satisfying the boundary condition of eqs. (10a) and (10b).

The energy conservation law requires for the total volume V and the partial volumes V_1 ($z < 0$) and V_2 ($z > 0$) the equality

$$\begin{aligned} \overline{\mathbf{E}_1^* \mathbf{E}_1} V_1 = & V_1 \left(\overline{\mathbf{E}_1^*}(z < 0) + \overline{\mathbf{E}_2^*}(z < 0) \right) \cdot \left(\overline{\mathbf{E}_1}(z < 0) + \overline{\mathbf{E}_2}(z < 0) \right) \\ & + V_2 \left(\overline{\mathbf{E}_1^*}(z > 0) + \overline{\mathbf{E}_2^*}(z > 0) \right) \cdot \left(\overline{\mathbf{E}_1}(z > 0) + \overline{\mathbf{E}_2}(z > 0) \right), \end{aligned} \quad (11)$$

where $\mathbf{E}_1(k, z)$ describes the incident wave ($k > 0, z < 0, z > 0$) and $\mathbf{E}_2(k, z)$, both the reflected wave ($k < 0, z < 0$) for and the penetrating wave ($k > 0, z > 0$). Finally, for the double layer under consideration we have to require that all time derivatives of \mathbf{E}_1 and \mathbf{E}_2 vanish for $z=0$.

$$\frac{\mathcal{I}^n \mathbf{E}_i}{\mathcal{I} t^n} = 0 \text{ for } z=0, i=1, 2, n=1, 2, \dots \quad (12)$$

This classical boundary condition requires the existence of a double layer where a vacuum is sandwiched between two layers of high, but opposite polarizability. This again can be realized by a small double layer of highly nonlinear polarizability. At the same time, the gradient of \mathbf{E}_1 and \mathbf{E}_2 in z direction has to be rather high at $z=0$, in order to satisfy the inhomogeneous eq. (5). By taking account of these boundary conditions one finds a rather general solution of eq. (5) which includes phase conjugation under destructive interference for $z < 0$ and constructive interference for $z > 0$. This solution takes the form

$$\mathbf{E}(\mathbf{r}, k, \mathbf{w}, z, t) = (\mathbf{J}(\mathbf{r})\exp(-i\mathbf{w}t) + \mathbf{J}^*(\mathbf{r})\exp(i\mathbf{w}t))(\exp(ikz) - \exp(-ikz)). \quad (13)$$

As it can be easily verified, for phase conjugation in the zone $z < 0$, the reflected beam $\mathbf{E}_2(\mathbf{r}, k, \mathbf{w}, z, t) = \mathbf{E}(\mathbf{r}, -k, \mathbf{w}, z, t) = \mathbf{E}^*(\mathbf{r}, k, \mathbf{w}, z, t) = -\mathbf{E}(\mathbf{r}, k, \mathbf{w}, z, t)$. Consequently, for $z < 0$ the solution provides for phase conjugation as well as for perfect destructive interference. It fulfills all the necessary boundary conditions, including $\mathbf{E}(\mathbf{r}, k, \mathbf{w}, z, t) = 0$ for $z=0$ for all k, \mathbf{w} , and t and the vanishing time derivatives in $z=0$. For $z > 0, k > 0, \mathbf{E}$ remains unchanged. Consequently, constructive interference takes place. Otherwise, the energy conservation law would be violated.

Under these boundary conditions, the general “standing-wave”-solutions (eq. (13)) provide phase conjugates in terms of interference strings with destructive interference at the outside of the system and, as a consequence, constructive interference within the system. It should be noted that there is no confinement to the spatial and temporal pattern outside $z=0$, which means that every modulation of the wave is based on destructive interference by the special boundary conditions of phase conjugation effects. This means, in addition, that this mechanism is able to serve as the ideal basis of a communication system between both biological systems and the outside world and between and even within living systems, where the receiver has simply to provide the boundary conditions in terms of shifting its double layers into one of the nodal planes of the incoming carrier waves while the “language” is free for expressing the total information by spatio-temporal modulations of the interference fringes. It is evident that this does not hold only for the optical range but

becomes obviously even more likely with increasing wavelengths. In this way, it may represent an evolutionary principle of nature.

3 Sucking force

The mechanism describes the capacity of a system using phase information to store and distribute energy. This process is not passive absorbance but an active process where energy is stored by constructive interference within the system against an energy gradient of removed energy at the outside. We call this process photon sucking. It is evident that this leads to a force which is defined by the gradient of stored to destructed energy between the inside and the outside. This force has the opposite direction to the force of the radiation pressure of the incoming wave. In order to calculate this sucking force we use for simplicity the model of a cavity with a resonator value Q which shall represent the relevant energy content of the photon sucking biological system.

The radiation pressure, p_m is identical to the energy density of radiation at the surface of the incoming wave that is $p_v = n_n h\nu$, where n_n is the spectral component of the photon density and $h\nu$ the photon energy. From the spectral radiation pressure one arrives at the spectral force

$$K_n = n_n F h n, \quad (14)$$

where F is the surface area of the target of the incoming wave.

The photon sucking force, on the other hand, has to be assigned to the energy gradient dU/dz , where U is the relevant part of the stored energy, defined by Q times the energy flow i which corresponds to the Poynting vector of the “destructive interference” outflow. Then we have

$$K_n = - \frac{\int}{\int z} U_n, \quad (15a)$$

$$U_n = \frac{1}{n} i_n Q_n, \quad (15b)$$

where $i_n = n_n \cdot cF \cdot h n$.

$$K_n = - \frac{\int}{\int z} \left(\frac{i_n Q_n}{n} \right) = - n_n F h n \left(\frac{Q_n \cdot I}{\Delta z} \right). \quad (15c)$$

We expect consequently that for $Q=1$ and a double layer of a thickness of wavelength I the photon sucking force is just compensating the radiation pressure. This is, as one can see from eq. (15c), actually the case. The force exceeds the radiation pressure by a factor $A=Q\lambda/(\Delta z)$, where Δz is the thickness of the double layer. Taking, for instance, the exciplexes of neighboured base pairs of the DNA as the effective double layer, we may have a strong and highly efficient photon sucking. Taking for sun rays a Q -value of 10^6 , corresponding to their coherence time t of some nanoseconds (where $Q=tn$) and taking for simplicity the thickness of the double layer of the order of the wavelength, one gets a photon sucking force which is 10^6 times higher than the radiation pressure of sun rays. This may be the reason for plants (like sunflowers) turning the surface area of parts always perpendicular to the sun light. Dependent on the Q -value and the thickness of the layer, the

photon sucking force for one photon is about $1.6 \cdot 10^{-14}$ N times A for a cell, where A is the amplification factor $QI/(\Delta z)$. This force may well come into the order of known attractive forces between cells which require a value A of about 100 in case that there is a permanent exchange of at least one photon between neighbored cells.

4 Quantum description

It is very likely that the mechanism of destructive interference by phase conjugation phenomena is based on quantum optics. Actually, the possibility of squeezing light provides a powerful tool of fixed phase relations for adjusting light to highly polarizable matter and *vice versa*. We are free to start with a boundary condition that shall define the effect of the double layer which has been introduced classically by eq. (10). We require that any two waves of amplitudes \mathbf{g} and $-\mathbf{g}$ shall interfere within the two layers which establish the boundaries of the vacuum state. We express this by means of the well-known displacement operator

$$D(\mathbf{g}) = \exp(\mathbf{g}\mathbf{a} + \mathbf{g}^*\mathbf{a}^\dagger),$$

where \mathbf{a}^\dagger , \mathbf{a} are the creation operator and annihilation operator, respectively. Now, destructive interference by phase conjugation shall be defined by the following requirement:

$$1/2(D(\mathbf{g})D(-\mathbf{g})) = D(0). \quad (16)$$

At first, let us note again that most suitable candidates for this mechanism are the exciplex states of biological matter, in particular those of the DNA. In fact, as soon as a photon excites one of the base pairs of the DNA, it gets squeezed between the two strands which are subjects of strong Casimir forces.

Second, an immediate consequence of eq. (16) is the violation of the semigroup law (which holds for a chaotic photon field) in a way that hyperbolic relaxation takes place. We have shown in several papers that hyperbolic relaxation of delayed luminescence is a general property of biological systems. Straight forward calculations prove this statement of hyperbolic relaxation. Apply $D(\mathbf{a})D(\beta)$ to eq. (16). Then we have

$$1/2(D(\mathbf{a} + \beta + \mathbf{g})D(\mathbf{a} + \beta - \mathbf{g})) = D(\mathbf{a})D(\beta). \quad (17)$$

The l.h.s. can be reformulated to give $1/2(D((\mathbf{a} + \beta)/2)D((\mathbf{a} + \beta)/2 + \mathbf{g})D((\mathbf{a} + \beta)/2 - \mathbf{g}))$ which, after the arbitrary choice of $\mathbf{g} = +$ or $-(\mathbf{a} - \beta)/2$ results finally in

$$D(\mathbf{a})D(\beta) = 1/2(D((\mathbf{a} + \beta)/2)D(\mathbf{a})D(\beta)). \quad (18)$$

Now, let us transform $D(\mathbf{g})$ by an unitary transformation $U(t, \mathbf{g})$ into time development operator

$$D(t) = \exp\left(-\frac{i}{\hbar} \int H dt\right), \text{ where } H \text{ is the Hamiltonian. } D(t) = U(t, \mathbf{g})D(\mathbf{g})U^\dagger(t, \mathbf{g}) \text{ which results in}$$

the corresponding equation of eq. (18):

$$D(t_1)D(t_2) = 1/2(D((t_1 + t_2)/2)D(t_1)D(t_2)) \text{ for any } t_1, t_2. \quad (19)$$

In contrast to chaotic states which follow $D(t_1)D(t_2) = D(t_1 + t_2)$ and consequently are subject to an exponential decay law, eq. (19) cannot be satisfied by exponential relaxation. However, hyperbolic

decay following $D(t) = D(0)/t$ fulfills exactly eq. (19), since

$$\frac{1}{t_1} \cdot \frac{1}{t_2} = \frac{1}{2} \left(\frac{2}{t_1 + t_2} \right) \left(\frac{1}{t_1} + \frac{1}{t_2} \right) \quad (20)$$

This makes it obvious that a necessary condition of photon sucking is the coherence of the field under consideration described by eq. (19) in addition to definite boundary conditions. It is worthwhile to note that this general condition (19) originating from eq. (16) is already sufficient for destructive interference of the reflected wave after phase conjugation.

Actually, any ket $|\mathbf{u}\rangle$ can be written in the form

$$|\mathbf{u}\rangle = 1/2(D(0) + T)|\mathbf{u}\rangle + 1/2(D(0) + R)|\mathbf{u}\rangle, \quad (21)$$

where the operators T and R are defined according to

$$T = +1/2 (D(\mathbf{g}) + D(-\mathbf{g})), \quad (22a)$$

$$R = -T. \quad (22b)$$

In view of eq. (16) and because of $R^2 = T$, $T^2 = T$ and $RT = R$, the first term on the r.h.s. of eq. (21) describes the penetrating part ($z > 0$), the second term the reflected part ($z < 0$) of the wave under examination. Straight-forward calculation shows that the expectation value of the penetrating part provides energy conservation while the expectation value of the reflected part vanishes in accordance to ideal destructive interference. At the same time we have $|\mathbf{u}\rangle^* = -|\mathbf{u}\rangle$ for the reflected part, thus satisfying as well the condition of phase conjugation as of perfect destructive interference. It is evident that any solution can be constructed in terms of the solutions of eq. (21), describing then the basis of phase conjugation as well as of destructive and constructive interference. It is not our goal to go here into more details.

However, a combination $f(\mathbf{a}, \mathbf{a}+)T + g(\mathbf{a}, \mathbf{a}+)R$ may then well describe the whole process of the interaction with the double layer. In addition, we would like to say that it is very likely that the quantum description of photon sucking in biological systems requires squeezed states^[14] since the flexibility in tuning the uncertainties of amplitude and phase of the electromagnetic field is a most powerful instrument of biological organization and communication. This could also explain why biophoton emission is limited to weak intensities, since only a few photons in the field allow the perfect application of non-classical light for communication.

5 Summary and discussion

In our model the waves under consideration describe a standing wave solution of the Maxwell equations which fulfills the boundary conditions and the energy conservation law at the same time. In view of the energy conservation, destructive interference in one part of the space (outside of the cells) has to get compensated by constructive interference in the other part (inside). This is a process which happens within a common coherence volume and has to be treated as an entity and not as a sequence of temporally different single events. Polarizable matter alone, like DNA solution *in vitro*, is not sufficient for constructive interference. As showed by the equations and the

special solution of the equations sufficient for the interference is (i) a nonlinearly polarizable double layer of distance small compared to the wavelength and (ii) a sufficiently long coherence time of the impinging wave under (iii) the definite boundary conditions. The sufficient condition of nonlinear polarization at the surface of the system is a well-known property of biological structures (membranes, ensembles of biomolecules). It should be mentioned here that Fröhlich^[15] was the first who pointed out the connections between coherence and extraordinary polarizability in biological systems.

In summary all the nonlinear phenomena of biophotons listed in this paper find a rather simple explanation from the interference model which can be traced back to the coherence of the biophoton field, basically understandable in terms of the Dicke theory. Since biological systems are optically thick media, the Dicke condition is always well satisfied as a necessary condition. In addition, the fact that the biophoton field is far from thermal equilibrium provides a further favourable condition for interference phenomena.

The organization of cells (including growth, differentiation, ..), and the “language” may become understandable in this model too. This effect can play a certain role not only between cells and organisms, but also within cells and between groups of biomolecules. Specific phase and frequency modulations may provide the language of the system under consideration.

From the quantum theoretical point of view, photon sucking may become optimized in the non-classical range. Minimum-uncertainty wave packets (squeezed states) allow the most efficient interference effects of standing waves.

Acknowledgements The authors would like to thank Prof. Bei Shizhang for his great support and encouraging the cooperation of the research. This work was supported by the National Natural Science Foundation of China (Grant No. 39770208).

References

1. Popp, F. A., Chang, J. J., Gu, Q. et al., Nonsubstantial biocommunication in terms of Dicke's theory, in *Bioelectrodynamics and Biocommunication* (eds. Ho, M. W., Popp, F. A., Warnke, U.), Singapore-London: World Scientific, 1994, 293—317.
2. Chang, J. J., Popp, F. A., Yu, W. D., Research on cell communication of *P. elegans* by means of photon emission, *Chinese Science Bulletin*, 1995, 40: 76.
3. Schamhart, D. H. J., van Wijk, R., Photon emission and the degree of differentiation, in *Photon Emission From Biological Systems* (eds. Jezowska-Trzebioatowska, B., Kochel, B., Slawinski, J. et al.), Singapore-London: World Scientific, 1987, 137—152.
4. Scholz, W., Staszkiwicz, U., Popp, F. A. et al., Light-stimulated ultra-weak photon reemission of human amnion cells and wish cells, *Cell Biophysics*, 1988, 13: 55.
5. Galle, M., Neurohr, R., Altmann, G. et al., Biophoton emission from *Daphnia magna*: A possible factor in the self-regulation of swarming, *Experientia*, 1991, 47: 457.
6. Vogel, R., Smuth, R., Weak light emission from bacteria and their interaction with culture media, in *Biophotons* (eds. Chang, J. J., Fisch, J., Popp, F. A.), Dordrecht-Boston-London: Kluwer Academic Publishers, 1998, 19—44.
7. Belousov, L., Louchinskaia, N. N., Biophoton emission from developing eggs and embryos: Non-linearity, wholistic properties and indications of energy transfer, in *Biophotons* (eds. Chang, J. J., Fisch, J., Popp, F. A.), Dordrecht-Boston-London: Kluwer Academic Publishers, 1998, 121—140.
8. Dicke, R. H., Coherence in spontaneous radiation processes, *Phys. Rev.*, 1954, 93: 99.

9. Popp, F. A., Li, K. H., Gu, Q. eds., Recent Advances in Biophoton Research and its Applications, Singapore-London: World Scientific, 1992, 1—47.
10. Popp, F. A., Li, K. H., Hyperbolic relaxation as a sufficient condition of a fully coherent ergodic field, International Journal of Theoretical Physics, 1993, 32: 1573.
11. Chwirot, B., Popp, F. A., White light induces luminescence from normal and temperature sensitive *Saccharomyces cerevisiae*, in Biophotonics Proceedings of International Conference Dedicated to the 120th Birthday of Alexander Gavrilovich Gurwitsch, Moscow State University, September 28 to October 2 (eds. Belousov, L., Popp, F. A.), 1994, Moscow: Bioinform Services Co., 1995, 211—220.
12. Musumeci, F., Scordino, A., Triglia, A., Coherence and biophoton emission as investigated on *Acetabularia acetabulum*, in Biophotons (eds. Chang, J. J., Fisch, J., Popp, F. A.), Dordrecht-Boston-London: Kluwer Academic Publishers, 1998, 109—120.
13. Chang, J. J., Yu, W. D., Sun, T. et al., Spontaneous and light-induced photon emission from intact brains of chick embryos, Science in China, Ser. C, 1997, 40(1): 43.
14. Bajpai, R. P., Coherent nature of biophotons: experimental evidence and phenomenological model, in Biophotons (eds. Chang, J. J., Fisch, J., Popp, F. A.), Dordrecht-Boston-London: Kluwer Academic Publishers, 1998, 323—339.
15. Fröhlich, H., Long range coherence and energy storage in biological systems, Int. J. Quant.Chem., 1968, 2: 641.