Designing parameters for the synthesis of devices based on the Quantum optoelectronics

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Abstract
Quantum Optoelectronics has recently been the subject of much interest and research activity. The present paper gives the designing parameters for the synthesis of the devices based on the Quantum optoelectronics, resides the technical analysis of the important concepts of this field, and a short qualitative review of the recent important studies. It is hoped that this paper should be useful to the new researchers entering the field and also the designers engaged in exploring the novel important applications.

Keywords: Quantum Optoelectronics, Quantum Electrodynamics, Spontaneous parametric down conversion (SPDC), Classical electromagnetic wave, Two photon interference , Quantum Optics.

Resumen
La optoelectrónica cuántica ha sido recientemente objeto de mucho interés e investigación. El presente documento proporciona los parámetros de diseño para la síntesis de los dispositivos basados en la optoelectrónica cuántica, también aporta el análisis técnico de los conceptos importantes de este campo, y una breve revisión cualitativa de los últimos estudios importantes. Se espera que este documento sea útil para los nuevos investigadores que incursionan en este campo, y también para los diseñadores que se dedican a la exploración de nuevas aplicaciones importantes.

Palabras clave: Quantum optoelectrónicos, Electrodinámica cuántica, Paramétrica espontánea de conversión hacia abajo (SPDC), Onda electromagnética clásica, Interferencia de dos fotones, Óptica cuántica.

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I. INTRODUCTION

It is now considered that the Quantum electronics is an offshoot of quantum optics, dealing with the phenomenon involving light and its interactions with matter. On the basis of the quantum theory, light is considered both as an electro-magnetic wave and as a stream of particles called photons (phenomenon called wave particle duality) traveling with the speed of light in vacuum, which are the quantum mechanical particles in the form of a wave function confined in a finite region, each particle carrying one quantum of energy equal to hυ (h is Planck's constant and υ is the frequency of the light).

The photons move in the form of a stream of particles, but their overall behavior is determined by a quantum wave function, which is a measure of the probability of the particles being present in a given location at a particular instant of time. In fact this energy of a single photon is exactly equal to a transition between discrete energy levels in an atom or other light emitting system, and interestingly, the material absorption of a photon is just the reverse process. It was the explanation of spontaneous emission that led to the prediction of the existence of stimulated emission, the very basis of the laser. Still, the actual inventions of the maser and laser were done many years later after the development of a method for producing the population inversion.

The concepts of quantum optics are explained by the use of statistical mechanics, in which light is studied in terms of the field operators for the creation and annihilation of photons, the subject being also termed as quantum electrodynamics.

It is now well understood that coherent state is an encountered state of the light field, mainly used to approximately describe the output of a single frequency laser well above the laser threshold, and is known to exhibit Poissonian photon number statistics. A coherent state can be transformed into a squeezed coherent state by certain nonlinear interactions, which exhibits Poissonian (super- or sub-) photon statistics.

The correlations of photon statistics between different beams explain the other important quantum aspects, *e.g.*

parametric nonlinear processes can generate twin beams, which implies that ideally each photon of one beam is associated with a photon in the other beam. Quantum effects on atoms and matter are considered in different manners.

Atoms are considered as quantum mechanical oscillators having discrete energy spectrum with the transitions between the energy eigen states, which are driven by the absorption or emission of light. The oscillator strength is dependent on the quantum numbers of the states. For the area of solid state physics, the effects of quantum mechanics on the behaviour of electrons in matter are considered, and their interactions with photons are studied. Thus, the energy band models of solid state physics are very important for understanding the process of the detection of light especially in case of a solid

The solid state physics is heavily based on taking into account the quantum mechanics, and also the study of electrons; which in fact is very crucial for understanding the concepts of electronics. The effect of the spin of the electrons has also been recently considered in the topic of spintronics [1-3] – an offshoot of electronics.

The subject of Quantum optics has evolved by contributions from the topics - Electromagnetism, Quantum Mechanics, Quantum Electrodynamics, and by the contributions of great scientists like Newton, Fresnel, Maxwell, Planck and Einstein about the particle and wave nature of light, and also by some conclusive experiments like:

(i) Young's: interferences for establishing that a light wave can be added or substracted, and is in the form of a Sinusoïdal wave;

(ii) Fresnel's: Mathematical theory of diffraction and interferences establishing the Scalar wave nature,

(iii) Fresnel-Arago: polarization phenomena, establishing the Transverse vectorial wave nature, and

(iv) Faraday-Maxwell's explanation of light as an electromagnetic phenomenon.

In the beginning, there were certain problems of understanding certain phenomena like-the spectral behaviour of black body radiation *e.g.* the decrease at high frequency, and the position of the spectral lines; and the photoelectric effect *e.g.* the UV light removes charges on the surface, whereas the visible light does not do so. The different approaches explained the different things:

(i) according to Planck, the energy exchange occurs in multiples of hν;

(ii) the Bohr's model is based on the atomic energy levels;

(iii) according to the Einstein's theory, Light is made of particles in the form of the unbreakable quanta of energy $E = h\gamma$.

This was checked by Millikan, and later on the Compton effect suggested that a photon of wavelength λ_0 on interaction with a crystal is scattered having a wavelength λ_1 not equal to λ_0. It is interesting to note that the electromagnetic field $E\left(r,t\right)$ in vacuum is not identically zero, and in fact varies in the form depicted below:

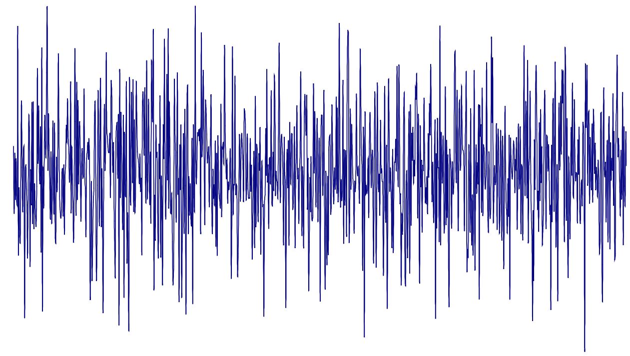

FIGURE 1. The representation of the electromagnetic field E (r,t) in vacuum.

It is clear that the field is null only on average, and there is clear existence of vacuum fluctuations. Thus, the excited levels of atoms are quite unstable; which is observed through a quadratic Stark effect, and also from the displacement of the excited levels by the vacuum fluctuations, producing the Lamb shift.

Quantum Electrodynamics (QED) serves as the base and model for all modern theoretical physics like - Elementary particles. The large success of quantum electrodynamics has been in predicting the properties of matter in the presence of vacuum, and a strong .agreement between theory and experiment. Also, the progress in optical techniques, led to the development of lasers, better detectors, and understanding of the non linear optics.

It is important to note that the interaction of the photons with electrons for absorption, spontaneous emission, and stimulated emission has also been considered as the basis of the understanding the laser operation, in the initial research and development of the laser systems. Presently, the quantum optics, and quantum optoelectronics are not so much based on atomic physics as on solid-state physics, especially in the studies connected with Quantum Hall effect and Quantum cellular automata. In these studies, statistics of the electromagnetic field like variance, and correlation functions form the basis of the discussion for understanding the nature of the source, whether thermal or Poissonian, and also the basic properties of astrophysical sources.

II. DESIGNING PARAMETERS FOR THE SYNTHESIS OF OPTOELECTRONIC DEVICES

The optoelectronics devices are designed on a large number of parameters, according to their application, and the spectral region of operation. The designing is so complex, that the designers also possess expertise in a particular device, besides having good knowledge about the similar devices.

Some designing aspects for some of the devices are technically discussed below:

A.1 Photoconductor quantum efficiency η_{PH}

The photoconductor quantum efficiency η_{PH} is one of the most relevant parameters for studying the performance and designing of some optoelectronic devices like photoconductors, and is easily obtained by following the treatment [4]:

$$\eta_{PH} = \frac{J_{PH}}{\left\{q.\phi'_{0}.(1-R)\right\}}, \qquad (1)$$

where J_{PH} is the photogenerated current density, R is the surface reflection coefficient and ϕ'_{0} is the spectral flow of photons in the photoconductor bulk. The photogenerated current density J_{PH} for the photoconductor can be easily computed from a modification of the current density at the emitter of a photodiode (4). The spectral flow of photons in the photoconductor bulk ϕ'_{PH} is computed by the following expression:

$$\phi'_{PH} = (1-e^{-\alpha d}).10^{16}.\{\frac{I_{0}\lambda}{19.8}\}, \qquad (2)$$

where α is the tabled wavelength-dependent silicon absorption coefficient, d is the photoconductor thickness.

A.2 Gain of an electron-multiplying CCD (EMCCD)

An electron-multiplying CCD (EMCCD, is a charge-coupled device, having a gain register placed between the shift register and the output amplifier, so that the gain register is split up into a large number of stages, in such a manner that In each stage, the electrons are multiplied by impact ionization , as is the case with an avalanche diode. The overall gain is given by:

$$Gain(G) = (1+P)^{N}, \qquad (3)$$

where P is the gain probability at every stage of the register, which is quite small $(P < 2\%)$, and . N is the number of elements, which being very large $(N > 500)$ results in a very high value of the overall gain, with single input electrons giving many thousands of output electrons. A problem encountered is that the gain that is applied in the gain register is stochastic, and therefore, the *exact* gain being applied to a pixel's charge is not exactly known. The designer has to guess this value based on his expertise and experience. Another observation is that at high gains (> 30), this uncertainty affects the signal-to-noise ratio (SNR) in the same way as halving the quantum efficiency (QE) with respect to operation with a gain of unity.

However, it has to be understood that at very low light levels, where the quantum efficiency is most important, it can be assumed that a pixel either contains an electron or does no contain it, which in fact removes the noise associated with the stochastic multiplication, though at the risk of counting multiple electrons in the same pixel as a single electron.

This problem of multiple counts in one pixel due to coincident photons in this mode of operation, can be avoided by having high frame rates. Theoretical and experimental investigations show that for multiplication registers with many elements and large gains; it is empirically modeled by the following expression:

$$P(n) = \frac{(n-m+1)^{m-1}}{(m-1)!(g-1+\frac{1}{m})^{m}\exp\left(-\frac{n-m+1}{g-1+\frac{1}{m}}\right)} \text{ if } n \geq m, \qquad (4)$$

Where P is the probability of getting n output electrons, corresponding to m input electrons and a total mean multiplication register gain equal to g. Hence, it is clear that the device has to be designed by optimizing the parameters P, n, m and g, which requires the skill and expertise of the designer, sometimes requiring the help from computer software.

A.3 Doped fibre amplifiers (DFAs)

Doped fibre amplifiers (DFAs) are special optical amplifiers, based on using a doped optical fibre as a gain medium for amplifying an optical signal, and in this way are related to fibre lasers.

The design is simple: multiplexing the signal to be amplified by application of a pump laser into the doped fibre, and then amplifying it through interaction with the doping ions. It is interesting to note that a lot of work in this direction has recently been reported on Erbium Doped Fibre Amplifier (EDFA), having the core of a silica fibre, doped with trivalent erbium ions, which is efficiently pumped with a laser at a wavelength of 980 nm or 1,480 nm, resulting in gain around 1,550 nm region.

Thus, it is clear that an erbium-doped waveguide amplifier (EDWA) is an optical amplifier, which uses a waveguide to boost an optical signal. Chopra [5] has made a detailed study of the diode pumped Er Fiber Lasers and discussed qualitatively some novel studies on them.

A.4 Parallel optical interface technology

Aparallel optical interface is a form of fiber optic technology, used mainly for communications and networking purposes at short distances (< 300 meters), for high bandwidths. These optical interfaces are different from traditional fiber optic communication in the sense that the data is simultaneously transmitted and received over multiple fibers. The data is split up over this high bandwidth link by using different methods, the simplest form, being the parallel optic link, which in fact is a replacement for many serial data communication links.

However, for more typical application, one byte of information is split up into bits and each bit is coded and sent across the individual fibers.

A.5 Photomulyipler technology

Just like the electricity, which is considered as electron current, light can be seen as a photon current, the respective fields being called electronics and photonics. The particle-photon possesses a given momentum, and in a photomultiplier, a large amount of multiplication takes place, by arranging a number of electrodes as shown in the Fig. 2.

It should be noted that the pulses recorded in the photomultiplier are due to the quantum jumps inside the material and not to the granular structure of light, in the same manner as in case of the photographic plate in Taylor's experiment. However, the effects like - Photoelectric Effect and Compton Effect are understood on the basis of a classical wave.

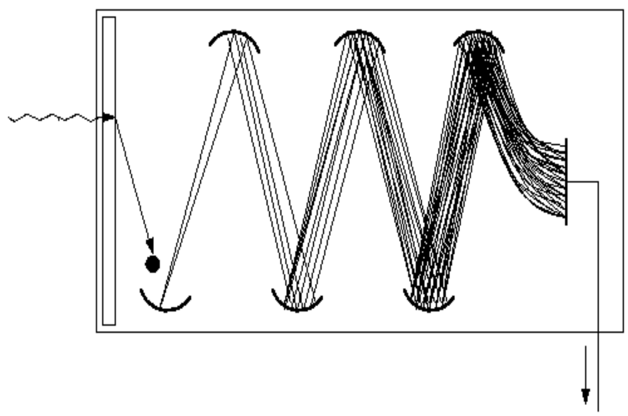

FIGURE 2. The schematic of a photomultiplier.

Whereas waves are continuous, nonlocalized, and breakable; the Photons are discontinuous, localized, and unbreakable. In a crucial experiment, the semitransparent plate showed that a photon is not cut into two. Interestingly, a very faint source does not produce a true one photon state.

However, a beam is a superposition of different states, *e.g.* a faint source does not give a clear result. Also, a single dipole (*e.g.* atom or ion) emits a single photon at a time. The first experimental proof of the particle nature of light was provided by the one photon interference. The non linear optics experiments performed showed that with a pump at frequency ω_0, the crystal generates twin photons at frequencies ω_1 and ω_2, with a perfect correlation between the two channels, besides the fact that the system behaves as an efficient source of single photon states. In addition, it is not possible to describe the resulting light in the form of the two classical waves emitted by a crystal described in a quantum manner.

Many different versions of light that have been accepted are:

(i) Light can behave like a classical wave *i.e.* Classical interferences;
(ii) Light can behave like a classical particle *i.e.* One photon interferences; and
(iii) Light can behave like a non classical state *i.e.* Two photon interferences.

A.6 Two photon multiplier by parametric down conversion

If the down converted light is made to pass through appropriate filters, it is possible to see both of the daughter photons called signal and idler. Particularly, we can choose to filter light, which has exactly twice the wavelength of the ultraviolet pump, the process being called the choosing of the degenerate down converted wavelength.

Photons of one polarization - signal are emitted in only one particular set of angles, and of the other polarization – idler, are emitted in another direction, corresponding to the momentum conservation. An interferometer using the photon pairs from the spontaneous parametric down conversion (SPDC) was first used to show the quantum nature of light; the schematic being called the Hong-Ou-Mandel dip experiment, as shown below:

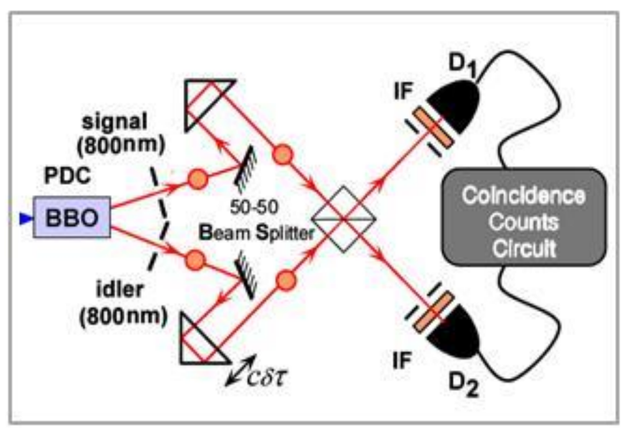

FIGURE 3. Hong-Ou-Mandel dip experiment for the generation of a photon pair by parametric down conversion (PDC); in which two photons are overlapped on a beam splitter spatially and temporally.

D_1 and D_2 are the detectors. In the SPDC apparatus design, a strong laser beam called the pump beam, is directed at a beta barium borate (BBO) crystal. It is observed that though most of the photons pass straight through the crystal, some of them occasionally, undergo spontaneous down conversion with type II polarization correlation (having perpendicular polarizations), so that the resultant correlated photon pairs have trajectories confined within two cones, with axes symmetrically arranged with respect to the pump beam. If one of the pair - the signal is detected at any time, then its partner - the idler is also known to be present.

The two photons are symmetrically located within the cones, because of the conservation of energy. Also, there is the possibility of the trajectories of the photon existing simultaneously in the two lines of intersection of the cones, thereby resulting in the entanglement of the photon pairs within the two lines w.r.t. the polarization.

Thus, it is clear that the SPDC is stimulated by the random vacuum fluctuations, resulting in the creation of the photon pairs at random times. It is to be noted that the single photons as well as the photon pairs are useful in quantum information experiments, and have applications like quantum cryptography.

Interestingly, it was observed that the coincidence counts dropped down when the path lengths of the photons became identical; which established the two photon interference.

A.6.1 Photon bunching (thermal nature in the process of SPDC)

SPDC is a process, in which the photons from a pump laser beams are randomly converted into pairs of photons at lower frequency, and thus creates the optical fields containing a single photon. This process is termed as photon bunching, in which the light consists of a stream of photons, with the photons clustered together in bunches.

The thermal nature of the field in one arm of a SPDC source has been studied, and the photon statistics of weak light pulse emitted in the process of pulsed parametric down-conversion have already been measured by using the arrangement shown below:

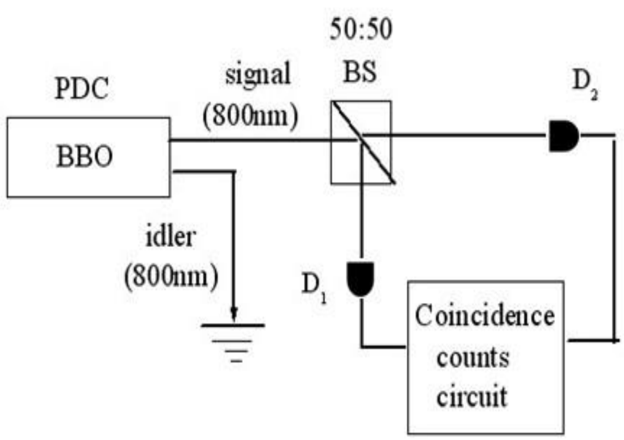

FiGURE 4. Schematic for studying the Photon bunching, showing the thermal nature in the process of SPDC.

A beam splitter is used for dividing the signal into two parts, half in the reflection and half in transmission. The circuit does the counting of the coincidence counts, which establishes the photon bunching.

A.7 Electric field of a few femtosecond flash

Planck gave the theory that light moves in discrete bundles *i.e.* photons; and Einstein expanded this by providing the explanation of the photoelectric effect to define the photon theory of light. With the development of the maser and laser, quantum optics began being used as the term for this specialized field of study.

Based on the findings of the quantum electrodynamics, quantum optics is interpreted in the form of the creation and annihilation of photons, described by field operators. The lasers and masers are obviously the most important applications of the quantum optics, since the light emitted from these devices is coherent, which means that the light closely resembles a classical sinusoidal wave.

Thus, the quantum mechanical wave function is distributed equally, and hence the light emitted from a laser is, highly ordered, and mostly limited to the same energy state *i.e.* the same frequency and wavelength. The variation of the light electric field with time is available in the literature, and has been reproduced below:

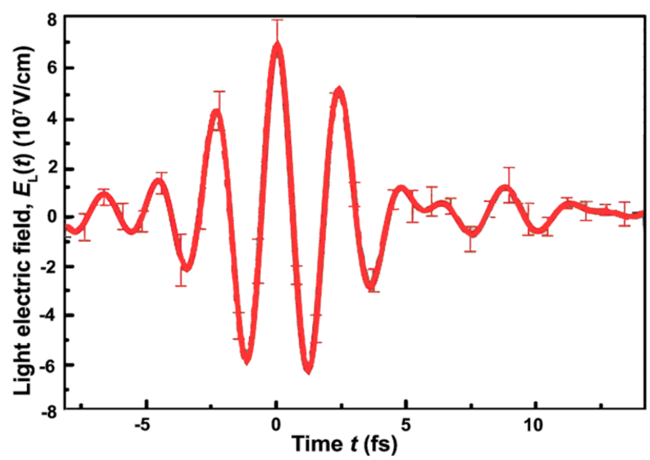

FiGURE 5. The electric field of a few femtosecond flash. Figure courtesy www.mpg.d.

The curve depicts the electric field of a few femtosecond flash of red light, as recorded by an apparatus called the attosecond oscilloscope. It is possible to measure the ultrabroad band light pulses (consisting of the many different colours), directly and accurately, leading to the reproducible synthesis of the ultrashort flashes of light with arbitrary waveform, which are useful for a number of applications including the development of molecular electronics and X-ray lasers.

A.7.1 Ultrafast electron sources

A very interesting phenomenon has been observed that on irradiating a field emission tip electron source with the femtosecond optical pulses, the electron packets with femtosecond duration are emitted from the tip. In the initial experiments, the primary tip source fabricated from Tungsten was used.

By trying other new shapes and tip materials like Gold or Silver, possibility of creating the sub laser cycle electron (attosecond) packets has been explored, which can be useful in a variety of experiments including those for testing the Electron Quantum Optics.

In the beginning, most of the quantum optics studies were based on the studies of the photon, a boson, and the related statistics, with very little effort on the use of the fermions and electrons for conducting the fundamental studies; especially the role of the free electrons in the experimental field of electron quantum optics being relatively unexplored, due to the obstacle that the available sources at that time were of very low degeneracy.

With the development of the new sources, which use the ultrafast femtosecond laser pulses to initiate electron emission from the nanometer tips, the degeneracy of the subsequent electron beam has been greatly increased, which has led to the efforts in developing fermionic analogues to extremely important photon quantum optics techniques, and thus providing a powerful tool in testing the dynamical theories of the quantum optics and the related optoelectronics devices. The schematic of the apparatus used for such studies is shown below:

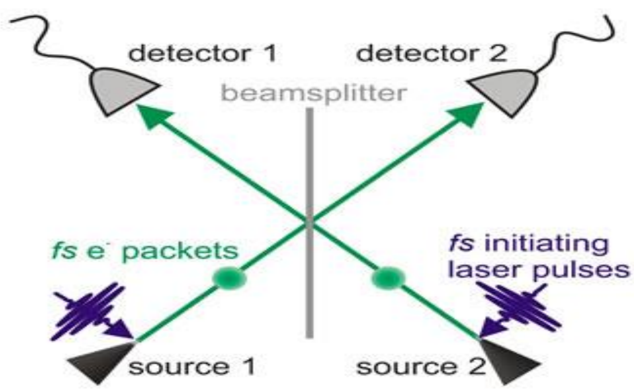

FIGURE 6. Ultrafast electron sources.

A.7.2 Electron pulse compressors

It is observed that the electron packets in vacuum disperse on traveling in vacuum, which results in the spreading of the electron packet in space, and hence having a longer duration, though with a decreased temporal resolution for experiments relying on the duration of the electron packet for studying the related dynamics.

This problem has been overcome by developing methods to compress the electron packets after their dispersion. Especially, the femtosecond laser pulses can be used for directly compressing a freely propagating electron packet, and thus making it possible to synthesize the attosecond electron packets.

III. SOME NOVEL STUDIES AND CONCLUDING RRMARKS

It has now been well established that the Quantum optics is the union of the quantum field theory and physical optics. The developments in this field have led to the progress in the fields of quantum computing, quantum cryptography and also in the development of the laser fundamental experimental studies on the foundations of quantum mechanics using quantum optics including the demonstrations of the entanglement, and teleportation.

Recently, momentum seems to have picked up in the studies [6, 7, 8, 9] on this interesting field. It is now well known that the generation of time-bin entangled photon pairs requires the use of the Franson interferometer which consists of two spatially separated unbalanced Mach-Zehnder interferometers through which the signal and idler photons from SPDC are made to transmit individually.

The scheme is known to work for the two SPDC pumping regimes: the narrowband regime and the double-pulse regime. Whereas in the first case, the SPDC process is pumped by a narrowband cw laser with the coherence length much longer than the path length difference of the Franson interferometer, in the second case, the longitudinal separation between the pulse pair is made equal to the path length difference of the Franson interferometer.

Gmachl [10] has discussed the ultrafast interaction of light with matter so that the communication can be done almost by using the semiconductor structures embedded in an optical microcavity.

Chopra [11] has discussed the modeling and designing aspects of the optical microcavities, and has also reviewed their novel applications.

Zrenner *et al.* [12] have discussed that the optical properties of semiconductor quantum dots are quite similar to those of atoms, since they can be defined by the state-of-the-art semiconductor technologies, and exhibit long-term stability besides allowing for the well-controlled and efficient interactions with both optical and electrical fields.

Zrenner *et al.* [12] have also shown that the resonant ps excitation of single quantum dot photodiodes leads to the new classes of coherent optoelectronic functions and devices, which exhibit precise state preparation, phase sensitive optical manipulations, and also the control of quantum states by electrical fields.

Quantum non-demolition (QND) measurements are known to improve sensitivity by evading measurement back-action.

Sewell *et al.* [13] have demonstrated a certified QND measurement of the collective spin of an atomic ensemble, by observing quantum-state preparation (QSP) and information-damage trade-off (IDT) beyond their classical limits by 7 and 12 standard deviations, respectively.

It has been emphasized that their techniques complement the recent work with microscopic systems, and can be used for quantum metrology and memory, the preparation and detection of non-Gaussian status, and quantum simulation and information purposes.

Photons are found to be the ideal carriers of quantum information for communication, and each photon can have a single or multiple qubits encoded in its internal quantum state, as defined by the optical degrees of freedom such as polarization, wavelength, and transverse modes. However, since the photons do not interact, multiplexing and demultiplexing the quantum information across photons has so far not been possible.

Vitelli *et al.* [14] have introduced and demonstrated experimentally a physical process, named 'quantum joining', in which the two-dimensional quantum states (qubits) of two input photons are combined into a single output photon, within a four-dimensional Hilbert space.

They have also proposed the inverse process, in which the four-dimensional quantum state of a single photon is split into two photons, each carrying a qubit. It has been claimed that both these processes can be iterated, and hence provide a flexible quantum interconnect to bridge multiparticle protocols of quantum information with multidegree-of-freedom, and with possible applications in future quantum networking.

Duarte [15] has written a book on Quantum Optics for Engineers, which provides a transparent, and methodical, introduction to Dirac's braket notation, derivation of the basic aspects of quantum mechanics such as Heisenberg's uncertainty principle and Schrodinger's equation, and illustrates the interferometric quantum origin of diffraction, refraction, and reflection.

Kwon *et al*. [16] have proposed another regime by which the generation of time-bin entanglement is possible, and have demonstrated the scheme experimentally. Their scheme is different from the previous approaches, in the sense that the SPDC process is pumped by a cw multi-mode *i.e.*, short coherence length laser and makes use of the coherence revival property of such a laser. It has been concluded that the high-quality time-bin entanglement source can be developed using inexpensive cw multi-mode diode lasers for various quantum communication applications.

Ramirez-Alarcon *et al.* [17] have presented a theoretical and experimental analysis of the joint effects of the transverse electric field distribution and of the nonlinear crystal characteristics on the properties of photon pairs generated by the SPDC. It is known that for a sufficiently short crystal, the pump electric field distribution fully determines the joint signal-idler properties; and for the case of the longer crystals, the nonlinear crystal properties play an important role.

Ramirez-Alarcon *et al.* [17] have presented the experimental measurements of the angular spectrum and of the conditional angular spectrum of photon pairs produced by the SPDC, carried out through the spatially resolved photon counting.

Lozovoy *et al*. [18] have carried out an analysis of tendencies of Ge on Si quantum dots nanoheterostructures' usage in different optoelectronic devices like, solar cells and photodetectors of visible and infra-red regions, and have described a complex mathematical model for calculation of dependency on growth conditions of self-organized quantum dots of Ge on Si grown using the method of molecular beam epitaxy parameters, by considering the ways of segregation effect and underlying layers' influence.

It has been shown that for realization of good device characteristics, quantum dots should have high density, small sizes, uniformity, and narrow size distribution function. It has been emphasized that the desirable parameters of arrays of square and rectangular quantum dots for device application are attainable under certain growth conditions.

In view of these novel studies, it can be concluded that the subject has been evolving fast, and also finding applications in the entirely new areas.

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REFERENCES

[1] Chopra, K. N., *A technical note on spintronics (An off - shoot of electronics). Its concept, growth and applications*, Atti Fond G. Ronchi **68**, 293-303 (2013).

[2] Chopra, K. N., *A short technological note on some novel concepts connected with spintronics*, Inv. J. Sc. Tech. **6**, 1-14 (2013).

[3] Chopra, K. N., *A short note on the mathematical modeling of spintronic devices*, Atti Fond G. Ronchi **68**, 39-54 (2013).

[4] Markvart & Castañer L., *Practical handbook of photovoltaics. Fundamentals and applications*, (Elsevier, Philadelphia, 2003).

[5] Chopra, K. N., *A Technical note on the diode pumped er fiber lasers and a short review of some important novel studies*, Atti Fond G. Ronchi **69**, 299-310 (2014).

[6] Goban, A., Choi, K. S., Alton, D. J., Ding, D., Lacroûte, C., Pototschnig, M., Thiele, T., Stern, N. P. & Kimble, H. J.,

Demonstration of a State-Insensitive, Compensated Nanofiber Trap, Phys. Rev. Lett., **109**, 033603 (2012).

[7] Chang, D. E., Jiang, L., Gorshkov, A. V. & Kimble, H. J., *Cavity QED with atomic mirrors*, New J. Phys. **14**, 063003 (2012).

[8] Hung, C.-L., Meenehan, S. M., Chang, D. E., Painter, O. & Kimble H. J., *Trapped atoms in one-dimensional photonic crystals*, New J. Phys. **15**, 083026 (2013).

[9] Chang, D. E., Cirac, J. I. & Kimble, H. J., *Self-organization of atoms along a nanophotonic waveguide*, Phys. Rev. Lett. **110**, 113606 (2013).

[10] Gmachl, C., *Quantum optoelectronics: Swift switch of the strong*, Nature **458**,157-158 (2009).

[11] Chopra, K. N., *A technical tutorial on the modeling and designing aspects of the optical microcavities and a short review of their novel applications*, Atti Fond G. Ronchi **64**, 737-748 (2014).

[12] Zrenner, A., Ester, P., Michaelis de Vasconcellos, S., Hübner, M. C., Lackmann, L., Stufler, S. & Bichler, M., *Coherent optoelectronics with single quantum dots,* J. Phys.: Condens. Matter **20**, 454210 (2008).

[13] Sewell, R. J., Napolitano, M., Behbood, N., Colangelo, G. & Mitchell, M. W., *Certified quantum non-demolition measurement of a macroscopic material system*, Nature Photonics **7**, 517-520 (2013).

[14] Vitelli, C., Spagnolo, N., Aparo, L., Sciarrino, F., Santamato, E. & Marrucci, L., *Joining the quantum state of two photons into one*, Nature Photonics **7**, 521-526 (2013).

[15] Duarte F. J., *Quantum optics for engineers* (Taylor and Francis, New York, 2014).

[16] Kwon, O., Park, K. K., Ra, Y. S., Kim, Y. S. & Kim, Y. H., *Time-bin entangled photon pairs from spontaneous parametric down-conversion pumped by a cw multi-mode diode laser*, Opt Express. **21**, 25492-500 (2013).

[17] Ramirez-Alarcon, R., Cruz-Ramirez, H. & U'Ren, A. B. *Effects of crystal length on the angular spectrum of spontaneous parametric downconversion photon pairs*, Laser Physics **23**, 055204 (2013), arXiv:1306.4903v1 [quant-ph].

[18] Lozovoy, K. A. , Voytsekhovskiy, A. V., Kokhanenko, A. P., Satdarov, V. G., Pchelyakov, O. P. & Nikiforov, A. I., *Heterostructures with self-organized quantum dots of Ge on Si for optoelectronic devices*, Opto-Electronics Review **22**, 171-177 (2014).