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Mid-infrared entangled photon generation in optimised asymmetric semiconductor quantum wells

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ABSTRACT

The optimal design of asymmetric quantum well structures for generation of entangled photons in the mid-infrared range by spontaneous parametric downconversion is considered, and the efficiency of this process is estimated. Calculations show that a reasonably good degree of entanglement can be obtained, and that the optical interaction length required for optimal conversion is very short, in the few μm range.

1. Introduction

Generation of entangled photons, and of heralded single photons, is a very important ingredient in a variety of quantum information technologies. Experimental implementation of these techniques, using optics, requires a reliable source of correlated/entangled and single photons. This is usually implemented by the spontaneous parametric downconversion (SPDC) process in a nonlinear optical medium with non-zero second order susceptibility, where the pump photon gets split into a 'signal' and 'idler' photon. The twin photons are usually polarisation-entangled. However, one can also use the spectral (frequency) entanglement of the photon pair.

In the visible or near-infrared wavelength range, the commonly used materials for this purpose are nonlinear optical crystals like lithium niobate, which have relatively large nonresonant nonlinear susceptibility. There are bulk materials which are good in the mid-infrared range, however at these longer wavelengths one can also take advantage of much larger resonant nonlinearities achievable in semiconductor heterostructures, based on intersubband transitions between size-quantized states therein. Second-order nonlinearity is available in asymmetric semiconductor quantum well (QW) structures. High nonlinearity appears in relatively narrow ranges of photon energies, near the transition resonances, which are typically in the mid-infrared range. In contrast to SPDC based on conventional nonlinear crystals, which enable different polarizations of signal and idler photons, and hence the polarization entanglement, a specific feature of Γ-valley intersubband transitions is

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that their nonlinearity exists only for light polarization perpendicular to the QW layer, hence disabling polarization entanglement. This type of SPDC is also known as a type-0 parametric process. Here we consider the design of high efficiency entangled photon sources by optimizing the profile of semiconductor quantum wells so as to obtain maximal second order nonlinear susceptibility, and consider the efficiency of spectrally entangled twin photon generation.

2. SPDC generation of twin photons in quantum wells

The SPDC process is illustrated in Fig. 1. The photon-pair generation is a second order nonlinear process in which a pump photon with frequency ω_p is spontaneously converted into two photons with lower energy, called signal and idler photons, with frequencies ω_s and ω_i respectively. The process is allowed in materials with non-zero second order susceptibility. Generally, resonantly enhanced susceptibility in quantum wells is accompanied by a large absorption, which in its own right, unrelated to phase-matching issues, leads to a limited useful interaction length in such structures.

Since SPDC is a second order nonlinear process, the polarization of SPDC is defined by Eq. (1)

$$\mathbf{P} = \varepsilon_0 \chi^{(2)} \mathbf{E}^2 \,. \tag{1}$$

The second-order nonlinear susceptibility ($\chi^{(2)}$) is calculated as [[1], p. 174]:

$$\begin{aligned}\chi^{(2)}(\omega_p+\omega_q,\omega_p,\omega_q) = \frac{e^3 N}{2\varepsilon_0 \hbar^2} \sum_{lmn} \left(\rho_{ll}^{(0)} - \rho_{mm}^{(0)}\right) d_{ln} d_{nm} d_{ml} \Bigg\{ & \frac{1}{[(\omega_{nl}-\omega_p-\omega_q) - i\Gamma_{nl}][(\omega_{ml}-\omega_p) - i\Gamma_{ml}]} \\ & + \frac{1}{[(\omega_{nl}-\omega_p-\omega_q) - i\Gamma_{nl}][(\omega_{ml}-\omega_q) - i\Gamma_{ml}]} \\ & + \frac{1}{[(\omega_{nm}+\omega_p+\omega_q) + i\Gamma_{nm}][(\omega_{ml}-\omega_p) - i\Gamma_{ml}]} \\ & + \frac{1}{[(\omega_{nm}+\omega_p+\omega_q) + i\Gamma_{nm}][(\omega_{ml}-\omega_q) - i\Gamma_{ml}]} \Bigg\} \end{aligned} \tag{2}$$

where ω_p and ω_q are the input, $\omega_p + \omega_q$ the output photon frequency, and Γ_{ij} are the linewidths. The total electron density is N, and $N\rho_{ii}^{(0)}$ is the electron density in quantised state i. The summation over lmn in Eq. (2) goes over all states in the system. The d_{ij} in Eq. (2) is the dipole transition matrix element, and for Γ-valley intersubband transitions it has only the z-component (perpendicular to the QW layer plane), so $\chi^{(2)}$ denotes the $\chi_{zzz}^{(2)}$ component of the susceptibility tensor.

Dipole matrix elements are calculated from the wave functions of states in the quantum well structure, obtained by solving the effective-mass Schrödinger equation. We have here used the effective-mass model with nonparabolicity, and the Schrödinger equation was solved by linearisation of the nonlinear matrix eigenvalue problem, as described in detail in Ref. [2]. In this case the d_{ij} cannot be calculated from the conventional expression $\langle\psi_i|\hat{z}|\psi_i\rangle$, as can be easily checked by varying the origin of the coordinate z (this changes the calculated values of d_{ij}, because of wavefunctions' non-orthogonality if the nonparabolicity is accounted for). Instead, the matrix elements of the momentum operator ($P_z = i\hbar \frac{d}{dz}$) are first calculated from Ref. [3]:

$$\langle\psi_i|\hat{P}|\psi_j\rangle = \frac{1}{2}\langle\psi_i\left|P_z\frac{m_0}{m(E_i,z)} + \frac{m_0}{m(E_j,z)}P_z\right|\psi_j\rangle \tag{3a}$$

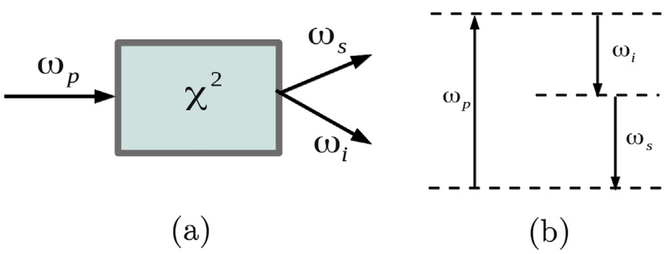

Fig. 1. Spontaneous Parametric Down Conversion Process (SPDC). (a) Geometry of SPDC, (b) Energy-level diagram describing the SPDC process.