Generation of entangled photons in Bragg reflection waveguides

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Abstract—**It will be shown that Bragg reflection waveguides can be used to generate entangled photons through the process of spontaneous parametric down-conversion. The design of the structure allows control of the dispersive properties of the modes that in turn control the properties of the generated photons.**

Keywords-Bragg reflection waveguides, entangled photons, spontaneous parametric down-conversion

An increasing number of quantum optics applications, ranging from quantum information processing and quantum communications to quantum metrology and quantum imaging, show enhanced capabilities when biphotons with quantum frequency correlations (entanglement) are used. A successful technological implementation of these new applications depends on the existence of efficient and robust sources that would offer a high flux of paired photons while they would allow tailoring the biphoton's quantum state for a particular application. The use of integrated structures to construct sources of entangled photons is straightforward as they greatly simplify the alignment and reduce the power requirements and costs.

It will be shown that $Al_xGa_{1-x}As$ Bragg reflection waveguides (BRW) can be employed to generate entangled photons through the nonlinear process of spontaneous parametric down-conversion (SPDC). Also, their design enables control of the bandwidth of the generated photons and, by extension, of their temporal correlations. Tailoring temporal correlations or spectral bandwidth is essential for practical purposes. Certain applications demand short correlation times such as clock synchronization and analogous quantum positioning and timing measurements. Other applications demand long temporal correlations or narrow spectral bandwidth, such as atom-photon interfaces or long-haul quantum communications.

$Al_xGa_{1-x}As$ waveguides are attractive because the current fabrication technology is mature, they have a large nonlinear coefficient, broad transparency window, large damage threshold, low linear propagation loss, and are convenient for integration [1]. They can also be monolithically integrated with a laser diode pump [2] which would eliminate the coupling difficulties. The main drawback of $Al_xGa_{1-x}As$ is its lack of natural birefringence. Birefringence is a very easy means to fulfill the phase-matching condition of the frequency-conversion process. Engineering techniques based on quasi-phase matching and artificial birefringence are widely used to achieve phase matching in III-V semiconductors.

The scheme employed here is based on Bragg reflection waveguides where exact phase matching between the frequencies involved in the nonlinear process can be achieved [3]. The properties of the generated entangled photons are given by the dispersive properties of the waveguide, including material dispersion, waveguide dispersion or a combination of both. Material dispersion is often controlled by temperature or electro-optic tuning which are in general weak in $Al_xGa_{1-x}As$. On the other hand, waveguide dispersion can significantly be controlled by a proper choice of the ridge width of the waveguide, which can easily be implemented with the help of standard lithographic techniques. The strong dependence of waveguide dispersion on the ridge width can serve to tailor the properties of the entangled photons generated using the SPDC.

In the SPDC process, a pump photon from time to time splits into two daughter photons whose energies sum up to that of the pump photon. The BRW's take advantage of the possibility of letting the pump mode propagate through Bragg reflection from periodic claddings while down-converted modes propagate by means of total internal reflection . In this way, it is possible to independently control the dispersive properties of the individual fields according to the needs of the application.

A representative ridge BRW along with typical intensity profiles of the pump and down-converted photons is schematically illustrated in Fig. 1. The periodic claddings

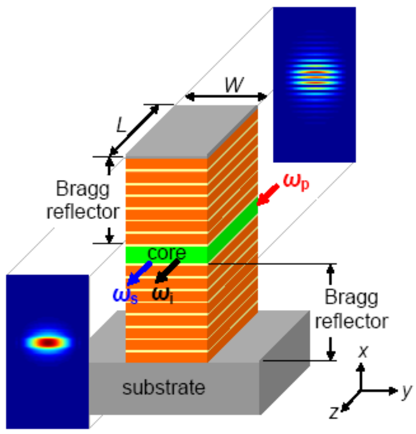

Figure 1. Schematic of a typical BRW with intensity profiles of the pump ω_p and of the downconverted photons ω_s and ω_i.

consist of 12 periods of $Al_{0.40}Ga_{0.60}As/Al_{0.90}Ga_{0.10}As$ with associated thicknesses of 89 nm/200 nm. The core is $Al_{0.65}Ga_{0.35}As$ with a thickness of 246 nm.

We assume the pump beam to be a continuous-wave source with frequency ω_p. The frequencies of the down-converted signal and idler photons are denoted as ω_s and ω_i, respectively. The two-photon state at the center of the nonlinear medium writes

$$|\Psi>=\int d\omega_s d\omega_i \Phi(\omega_s,\omega_i) a_s^\dagger(\omega_s) a_i^\dagger(\omega_i)|0\rangle_s|0\rangle_i \text{, where} \quad (1)$$

$$\Phi(\omega_s,\omega_i)=E_p(\omega_s+\omega_i)\,\mathrm{sinc}(\Delta_k L/2), \quad (2)$$

$E_p(\omega_s+\omega_i)$ is the frequency amplitude distribution of the pump beam, L is the sample length and $\Delta_k = k_p - k_s - k_i$ is the phase-mismatch function with k_j being the longitudinal component of the pump, signal and idler wavevectors, respectively.

Expanding the *k*-vectors in a Taylor series about the central wavelength, we can see the phase mismatch, and so the joint spectrum of the down-converted photons, is a function of the group velocities, group velocity dispersion and higher dispersive terms of the interacting fields. These parameters can expediently be controlled by the ridge width, $Al_xGa_{1-x}As$ composition, etch depth or the thicknesses of the Bragg layers. Only by changing the ridge width of the waveguide, it is possible to tailor the spectra of entangled photons over more than 2 orders of magnitude – from extremely broad spectra of hundreds of nanometers around the central wavelength of 1550 nm to very narrow spectra of less than 1 nm [4].

Figure 2 shows the dependencies of the phase-matching wavelength and the group velocity dispersion on the ridge width with the generated spectrum for one specific ridge width for type-I phase matching. The large bandwidth of 61 THz can be translated into a very narrow correlation time of some 15 fs.

Changing the ridge width and using type-II phase matching, a very narrow spectrum of the order of 1 nm can be obtained. On the other hand, the type-I structure used to generate the broad spectrum mentioned above can also be used to produce a narrow spectrum. It was designed to satisfy type-II phase matching as well and by only rotating the pump polarization we can reduce the spectrum from 450 nm to 5 nm.

Currently, an experiment is under way to generate down-converted photons. A single-frequency laser at 775 nm illuminates a spatial light modulator (SLM) that encodes a computer-generated hologram (CGH) to form an

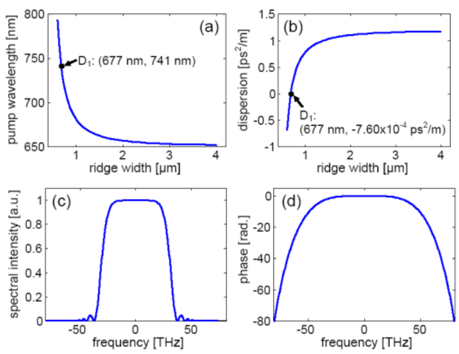

Figure 2. (a) Pump wavelength versus ridge width. (b) Signal group velocity dispersion versus ridge width. (c) Normalized joint spectral intensity $|\Phi|^2$ with a FWHM bandwidth of ~ 61 THz (~ 456 nm). (d) Phase of the spectral amplitude.

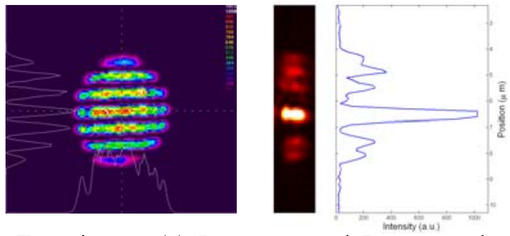

Figure 3. Experiment. (a) Reconstructed Bragg mode before the input coupling stage using an SLM. (b) Profile of the pump mode at the output facet of the waveguide along with the transverse intensity profile.

image with the form of the Bragg mode of the size of ~ 1 mm. An optical system reduces the size of this image 1000 times and couples it into the waveguide. The position and angle of the waveguide with respect to the optical setup are adjusted by piezoelectric elements. The generated photons are collected by an objective, separated by a beamsplitter and fed into a pair of InGaAs/InP avalanche photodiodes to detect coincidental counts. A picture of the Bragg mode formed in the air before the coupling stage is shown in Fig. 3(a). Figure 3(b) shows a picture of the output facet of the waveguide taken by a CCD camera with the coupled Bragg mode mixed with the fundamental Gaussian mode.

Recent success in developing an integrated edge-emitting Bragg reflection waveguide laser [2] is expected to remove the need for the preparation of the Bragg mode using the SLM, as the output mode of the Bragg laser becomes directly the input pump mode of the down-converting waveguide.

In summary, it has been shown that Bragg reflection waveguides can be used as compact, low cost and efficient source of entangled photons. By a suitable design of the structure it is possible to tailor the properties of the generated photons according to the needs of the application. Integration of the waveguide together with a Bragg reflection laser will provide a robust source of entangled photons. Currently, an experiment is under way to confirm the theoretical results.

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