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Abstract

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Reference


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Integrated AlGaAs source of highly indistinguishable and energy-time entangled photons

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The generation of nonclassical states of light in miniature chips is a crucial step toward practical implementations of future quantum technologies. Semiconductor materials are ideal for achieving extremely compact and massively parallel systems and several platforms are currently under development. In this context, spontaneous parametric downconversion in AlGaAs devices combines the advantages of room temperature operation, possibility of electrical injection, and emission in the telecom band. Here we report on a chip-based AlGaAs source, producing indistinguishable and energy-time entangled photons with a brightness of $7.2 \times 10^6$ pairs/s and a signal-to-noise ratio of $141 \pm 12$. Indistinguishability between the photons is demonstrated via a Hong–Ou–Mandel experiment with a visibility of $89 \pm 3\%$, mainly limited by the reflectivity of the chip facets, while energy-time entanglement is tested via a Franson interferometer leading to a visibility of $96 \pm 4\%$. © 2016 Optical Society of America

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Photonics is playing a key role in the development of future quantum technologies. Thanks to their propagation speed and long coherence time, photons are the most promising support for quantum communications [1]. Moreover, integrated photonics technology enables the development of on-chip platforms for demanding applications of quantum simulation [2], computation [3], and metrology [4] and allows critical problems to be solved in terms of scalability and reliability [5]. In this context, semiconductor materials may play a critical role; in particular, the generation of entangled photon pairs has been demonstrated using biexciton cascade in quantum dots [6,7] and nonlinear interaction in AlGaAs [8–10] or silicon-based devices [11–13]. The target property of the generated quantum state depends on the intended application; photons indistinguishability is at the heart of controlled logic gates [14], quantum networking [15] and boson sampling [16]. Entanglement is used to speed up algorithms [17], protect encoded information [18], teleport quantum states [19], and reduce intrinsic uncertainty in interferometry measurement [20]. For these reasons, sources producing different quantum states while maintaining a high degree of compactness and integrability are highly desirable. GaAs and its material derivatives like AlGaAs present a strong case for the miniaturization of different quantum components in the same chip [21]. Its direct bandgap has already led to the monolithic integration of the primary laser source and the nonlinear medium into a single device emitting photon pairs under electrical injection at room temperature [22]. Moreover, GaAs strong electro-optical Pockels effect enables a fast control and manipulation of the generated photons, as recently demonstrated [23]. On the front of on-chip single photon detection as well, high-efficiency superconducting nanowire single-photon detectors have been integrated with GaAs waveguides [24]. All of these achievements consolidate the potential of this platform to realize miniature chips containing the generation, manipulation, and detection of quantum states of light.

In this Letter, we present an AlGaAs ridge waveguide producing highly indistinguishable and entangled photon pairs at telecom wavelengths and room temperature. Our device has been optimized for efficient type-II spontaneous parametric downconversion (SPDC); two Bragg mirrors provide both a photonic bandgap confinement for a transverse electric (TE) Bragg mode at 783 nm [25,26] and total internal reflection claddings for $TE_{00}$ and $TM_{00}$ modes at 1.56 μm. The sample is grown by molecular beam epitaxy on a (100) GaAs substrate. It consists of a 6-period $Al_{0.80Ga_{0.20}As}$ Bragg reflector (lower mirror), a 298 nm $Al_{0.45}Ga_{0.55}As$ core, and a 6-period $Al_{0.25}Ga_{0.75}As/Al_{0.80}Ga_{0.20}As$ Bragg reflector (upper mirror). Waveguides are fabricated using wet chemical etching to define 5.5–6 μm wide and 5 μm deep ridges along the (011) crystalline axis in order to exploit the maximum nonzero optical nonlinear coefficient and a natural cleavage plane. Optical propagation losses in the telecom
range of 0.3 and 0.5 cm$^{-1}$ for the TE$_{00}$ and TM$_{00}$ modes, respectively, are measured via a standard Fabry–Perot technique. For this, we use a cw tunable laser (Tunics) to measure the transmitted signal at the output of the sample as a function of the wavelength [27]. This result is the state of the art for AlGaAs and of the same order of that measured in Si-based platforms.

The ability of our device to produce indistinguishable photons is tested through a Hong–Ou–Mandel (HOM) experiment [28]; in this type of measurement, two indistinguishable photons enter a 50/50 beam splitter at the same time. The destructive quantum interference makes them exit the beam splitter through the same output, thus inducing a dip in the coincidence histogram. Figure 1 shows a sketch of the experimental setup used for this experiment. The light beam of a cw Ti:Sa laser is used to excite the Bragg mode of the sample; after a spatial shaping with a holographic mask, it is injected into the waveguide with a microscope objective. Light emerging from the opposite end is collected with a second microscope objective, a fiber coupler, and filtered with a tunable fibered Bragg grating (FBG) having a full width at half-maximum (FWHM) of 10.8 nm.

The optimum working point of our source is determined by measuring the temporal correlations between the TE and transverse magnetic (TM) photons. Two Stirling-cooled free running single-photon avalanche photodiodes connected to a time-to-digital converter (TDC) are used for coincidence counting [29]. Figure 2 shows a histogram of the recorded detection time delays at temperature $T = 20.1^{\circ}$C for an internal estimated pump power of 625 $\mu$W in the guided mode. The coincidence to accidental ratio (CAR), an important figure of merit for a photon pair source, is calculated by taking the number of true coincidences within the FWHM of the peak over the background signal, on the same time window taken apart from the peak. The dependence of the CAR on both the pump wavelength and the internal pump power has been studied; a maximum value of the CAR of 141 ± 12 is obtained for a pump wavelength around 783 nm and an internal pump power around 625 $\mu$W, leading to a brightness of $7.2 \times 10^6$ pairs/s. This working point corresponds to the phase-matching resonance of the device. For a pump wavelength above the degeneracy point, the phase-matching condition is no longer satisfied and below degeneracy a shift of 0.2 nm results in a variation of 100 nm for the signal and idler wavelengths, which are, by consequence, outside the interferential filter. The CAR value, limited by the detector's dark counts, is the maximum ever obtained on a semiconductor waveguide, to our knowledge; this is due to the low value of optical losses of our sample and the low level of noise of the detectors employed in this work.

After the identification of the optimum working point, we proceeded to the HOM measurement. For this we used a polarization controller to align the polarizations of the photons and we inserted an interferometer with an optical delay line on one of the two arms, followed by a 50/50 beam splitter before the detectors. Figure 3 reports the dip observed in the coincidence counts as a function of the optical path length difference between the two arms of the interferometer. This dip is a clear signature of the destructive quantum interference between the two photons. The shape of the dip is given by the convolution of the two wave functions within the FWHM of the peak over the background signal, on the same time window taken apart from the peak. The dependence of the efficiency on both the pump wavelength and the internal pump power has been studied; a maximum value of the CAR of 141 ± 12 is obtained for a pump wavelength around 783 nm and an internal pump power around 625 $\mu$W, leading to a brightness of $7.2 \times 10^6$ pairs/s. This working point corresponds to the phase-matching resonance of the device. For a pump wavelength above the degeneracy point, the phase-matching condition is no longer satisfied and below degeneracy a shift of 0.2 nm results in a variation of 100 nm for the signal and idler wavelengths, which are, by consequence, outside the interferential filter. The CAR value, limited by the detector's dark counts, is the maximum ever obtained on a semiconductor waveguide, to our knowledge; this is due to the low value of optical losses of our sample and the low level of noise of the detectors employed in this work.

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$$N_c = A \left( 1 - V \times \text{sinc} \left( 2\pi \delta \frac{\delta t \pi}{\Lambda} \right) \right),$$

where $N_c$ is the coincidence rate, $A$ is the coincidence rate apart from the bunching region, $V$ is the visibility, $\delta t$ is the time delay,
and $\delta \lambda$ is the FWHM spectral intensity. The two fitting parameters are $\delta \lambda$ and $V$; for the first one we obtain $10.7 \pm 0.2$ nm, which is in very good agreement with the FBG filter FWHM, while for the second one we obtain a net (raw) visibility of 89.0 $\pm$ 2.8% (86.1 $\pm$ 2.7%). This result is an unprecedented value in a semiconductor waveguide; the limitation to the visibility in our experiment can be attributed to the reflectivity $R$ of our waveguide facets, which is around 24% for the TE and TM modes. Thus, a coincidence event can not only be due to two photons directly transmitted by the facets, but also to one photon directly transmitted and one photon having experienced two reflections before leaving the waveguide. Since in the latter case the path difference for the two photons is not the same as for the former case, these photons do not contribute to the dip [30]. In this case, the maximum achievable visibility is given by

$$V = \frac{1}{1 + R^2 (\eta_{TM} + \eta_{TE})} = 90.5\%,$$

where $\eta_{TM}$ and $\eta_{TE}$ correspond to the transmission efficiency for the two polarization modes in the sample. This expression is in excellent agreement with our experimental results. Standard telecom antireflection coating on the facets of AlGaAs waveguides allows to reach transmittivities of almost 100%; this kind of treatment applied to our device would thus increase the indistinguishability of the emitted photons.

Among different possible entangled states, we have chosen to produce energy-time entangled photons; this is a very convenient format of entanglement, as it can be easily manipulated with integrated circuits and can be preserved over long distances in standard optical fibers [31]. By pumping the device with a cw laser, the photon pairs are emitted simultaneously, but their emission time is undetermined within the coherence time of the pump laser. This lack of information leads to energy-time entangled pairs, as first pointed out by Franson [32]. We have thus implemented the experimental setup sketched in Fig. 1(b). Before passing through the polarizing beam splitter, the two entangled photons are directed into an unbalanced interferometer. A piezo actuator is used to control the relative phase $\phi$ between its short and long arm. An essential condition to fulfill in a Franson type experiment is that $(\tau_s, \tau_{det}) \ll \Delta \tau \ll \tau_p$, where $\tau_s$ is the coherence time of the signal and idler photons, $\tau_{det}$ is the jitter of the detectors, $\Delta \tau = \Delta l/c$ is the time difference between the two paths of the interferometer, and $\tau_p$ is the pump laser coherence time. As shown in Fig. 3, the coherence time of the photons is 0.7 ps. We have thus chosen a path-length difference of the interferometer of 2.5 ns, which is also much smaller than the 1 $\mu$s of coherence time of the cw laser pump (TOPTICA DL 100) and bigger than the timing jitter of the detectors (200 ps).

As shown in Figs. 4(a) and 4(b) the recorded histogram has three coincidence peaks; the left and right peaks correspond to a situation when one photon goes through the short arm ($s$) and the other through the long arm ($l$) of the interferometer. The middle peak results from the interference between the state where both photons pass through the short arm and the one where both photons pass through the long arm. This peak results from the quantum interference of the post-selected state,

$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|s\rangle|s\rangle + e^{i2\phi}|l\rangle|l\rangle),$$

where the indices $s$ and $l$ stand for signal and idler.

By a sinusoidal curve having a net (raw) visibility of 95.6 $\pm$ 3.7% (91.5 $\pm$ 3.6%), which corresponds to a fidelity of 97.8 $\pm$ 1.9%.

In conclusion, we have demonstrated an AlGaAs device working at room temperature with proven compliancy with electrical pumping [22], generating photon pairs linked by a high degree of
entanglement and able to interfere on a beam splitter with high visibility. The only solid state source featuring both of the last two properties demonstrated up to now is based on single quantum dot technology [33]; with respect to that result, our device presents the advantage of working at room temperature and displaying higher values of HOM and Bell visibilities. The present results constitute a step toward on-chip large scale photonic circuit-based quantum computation and simulation. They set the AlGaAs platform in an advantageous position for the development of monolithic complex architectures exploiting photon pair generation by electrical injection and fast quantum state manipulation via the electro-optics effect. Moreover, the recent progress in hybrid integration of III-V compound semiconductors onto silicon-on-insulator substrates allows for combining the advantages of our device to a nearly complete suite of silicon photonics components. These include filters, (de)multiplexers, splitters, interferometers, and photodetectors for the fabrication of novel generations of CMOS compatible chips for quantum information technologies.

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