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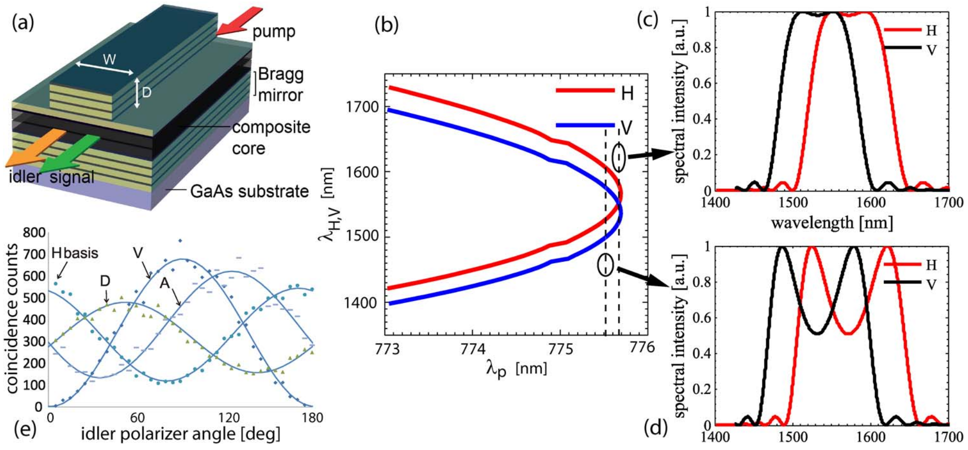

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Breakthroughs in Photonics 2013: Electrically Pumped Semiconductor Entangled Sources

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(Invited Paper)

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Abstract: Recent advances enabling the realization of room-temperature electrically injected chip sources for entangled photons will be highlighted and discussed. Emphasis will be placed on monolithic and hybrid integration settings that enable room-temperature and self-contained operation through electrical current injection. Compound semiconductors, as well as hybrid integration platforms such as those utilizing Si-on-insulator technology, play a central role in defining the approaches sought to realize these sources.

Index Terms: Entangled sources, integrated quantum photonics, monolithic nonlinear optics, parametric optoelectronic devices, quantum optics, quantum internet, semiconductor lasers, entanglement.

1. Introduction

Quantum states of light offer unique abilities to provide enhanced performance and novel capabilities to numerous domains of application. For example, in the domain of spectroscopy, pump-probe optical spectroscopy with entangled photons can yield unique insights into delocalization of excitons because of how the entangled photons can uniquely suppress single exciton features within the measurements [1]. As dictated by the laws of physics, the inability to perfectly reproduce a quantum system without destroying the original version enabled the development of fundamentally secure encryption schemes in communication systems [2]. In addition, the quantum mechanical properties of squeezed and entangled photon states can be exploited to access imaging resolutions that surpass the classical limits [3]. Despite their powerful, numerous and unique capabilities, quantum photonic technologies have not seen a proportional adoption in practical applications. Such a proliferation has been severely hampered by the form factor, mechanical sensitivity and cost of existing systems on offer.

The vast majority of sources of entangled photons have been constructed in-part using discrete optical components, thus requiring careful alignment with stringent stability requirements. Such a setting can be bulky, prohibitively expensive, extremely challenging to align and maintain aligned, thus confining the technology to especially equipped laboratories. It is therefore essential for quantum optical components and subsystem to move toward a more practical platform in order to attain their full potential. Integrated components and the associated subsystems also serve to enhance the scalability of many of the associated functions, particularity to those components pertinent to information processing for application domains such as quantum computing and quantum Internet.

Entangled sources in optical fibers have been recently reported with extremely promising performance [4]. Entangled sources in an array of InGaAsN quantum dots (QD) have also been reported [5]. Strain-free GaAs QDs that are self-assembled on a triangular symmetric (111)A surface have also been used as a source for entangled photons with a fidelity to the Bell state as high as 0.86 [6]. While these demonstrations hold significant promise for compact sources, in this report only the recent advances in the quest for realizing room temperature, electrically injected, chip sources for entangled photons using monolithic and hybrid integration settings will be reviewed.

2. Routes to Integration

Semiconductors are often used as sources of photon pair generation with the ultimate aim of electrical injection, integration and scalability. Recently quantum dots, placed in a cavity and optically pumped with a picosecond laser, have been reported to generate single photons with 0.97 visibility in a Hong–Ou–Mandel (HOM) interferometer without post-selection [7]. However, there is one method that has been used, more often than all its counterparts, to produce entangled or hyperentangled photons. This method relies on the nonlinear optical process of spontaneous parametric down-conversion (SPDC) in crystals with a second-order susceptibility $\chi^{(2)}$. Photon pairs generated via SPDC may have many degrees of freedom to utilize. Those include spatial mode, polarization, frequency, time, linear momentum and orbital angular momentum.

There is rich variety of nonlinear crystals which has been explored for generating entangled photons via SPDC. Some of these crystals are also capable of accommodating waveguides, where SPDC can take place upon optical pumping. In these waveguide sources, the photon pair generation rates are increased by orders of magnitude over their bulk crystal counterparts, and the use of well-confined waveguide modes facilitate the utilization and collection of generated photons. There has been a remarkable interest in the generation of entangled and hyperentangled photons in waveguides to enable integration. The most effective platform for such applications is periodically-poled lithium niobate (PPLN) and potassium titanyl phosphate (PPKTP) waveguides. Phase matching (PM) in PPLN, for example, makes use of quasi-phase matching (QPM) to provide access to the highest nonlinear coefficient of the material [8].

Waveguides made of PPLN and PPKTP offer an effective platform for realizing entangled and hyperentangled photons. However, these ferroelectric materials cannot be monolithically integrated with other photonics devices such as pump lasers, detectors and amplifiers on the same chip. While electrical injection is not possible in ferroelectric materials, it is most practically achieved in III-V semiconductor systems, where nonlinear optical structures can be integrated with both active and passive photonic components. The main hindering block in such implementations is the capability to effectively PM second order nonlinearities in compound semiconductor systems, which are extremely dispersive. Numerous strategies have been developed to achieve PM in semiconductor waveguides [9].

The most recent progress in efforts utilizing SPDC and other approaches such as QDs to realize room temperature, electrically injected and monolithically integrated entangled photon sources will be reviewed next.

2.1. Entangled Sources via Hybrid Integration Approaches

Hybrid integration provides a proven route to integration of entangled sources. This is because one is able to use the best performing component for each function, such as pair generation, pump, filtering, among others. One is then able to integrate them all for a superior source performance in a hybrid platform. This approach involves fewer compromises on the device performance front, but demanding requirements on the integration technologies. Active-passive integration has already been developed for the Si-on-insulator (SOI) platform to benefit numerous applications including

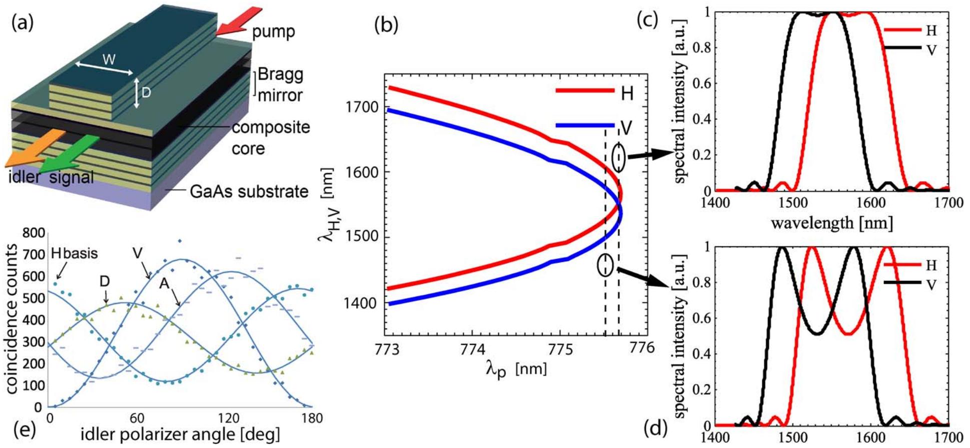

Fig. 1. (a) Illustration of SPDC in a BRW. (b) Theoretical tuning curves, with the dashed lines indicating pump wavelengths. (c) and (d) Theoretical spectra of H and V polarized single photons when the pump is at degeneracy, and 0.15 nm lower than degeneracy, respectively. (e) Visibility measurements in the HV and AD basis.

optical transceivers. Therefore, it is relatively straightforward to integrate semiconductor lasers with entangled photon sources that were originally developed on SOI for optical pumping.

The prevalence of Si for electronic devices, and recently optoelectronic devices, has provided a formidable technological platform enabling the utilization of the third-order susceptibility $\chi^{(3)}$ in this material system to offer optically pumped entangled photon pairs in a SOI platform [10], [11]. Prior to the aforementioned demonstrations an entangled photon source was also developed on SOI, where a Si wire waveguide acted as a photon pair source which operates only for the TE mode [12]. A polarization-dependent photon pair source was used to build a polarization entangled source by compensating for the polarization-dependent walk-off. The polarization rotator was placed in the middle of the structure yielding an entangled state with a fidelity of 0.91.

2.2. Entangled Sources via Monolithic Approaches

To be able to monolithically integrate an electrically injected pump within the structure of an entangled source, semiconductors tend to be the integration platform of choice. A few approaches have been pursued using semiconductors.

2.2.1. Entangled Sources Using Bragg Reflection Waveguides

Recently, it was demonstrated that the gallium–arsenide (GaAs)-based Bragg refection waveguide (BRW), as schematically shown in Fig. 1(a), could efficiently entangled produce photon pairs via SPDC [13], [14]. Its design was shown to have a distinct advantage over other semiconductor sources, due largely to its monolithic architecture and its layered epitaxy which underpins many photonic devices. The intrinsic capability of the BRW platform to directly produce polarization entangled photon pairs, without any additional interferometry, spectral filtering, compensation or post-selection as has been shown recently. Not only can BRW produce entangled photons, but this can be achieved without the traditional compensation and interferometric methods used to create entanglement, which take place on chip.

In this recent demonstration non-degenerate type-II SPDC process was utilized. The root cause of entanglement generation is the lack of birefringence in GaAs, which otherwise makes exact PM impossible in bulk crystals. Because of this, cross-polarized photons propagate at almost identical group velocities, making off-chip path compensation unnecessary. In addition, two concurrent processes coexist: The high frequency (signal) and low frequency (idler) photons can be either horizontally (H) and vertically (V) polarized, respectively, or vice versa, according to the theoretical tuning curves shown in Fig. 1(b). Although the two curves in Fig. 1(b) do not overlap due to a small

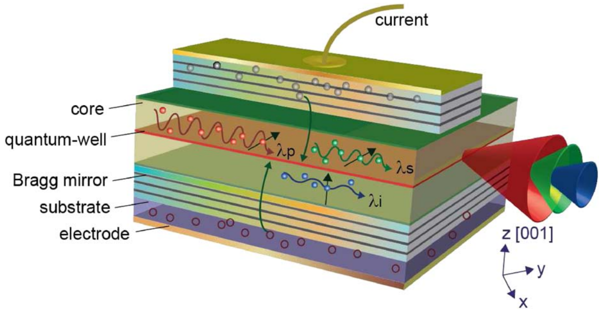

Fig. 2. A schematic describing the electrically injected entangled photon sources using Bragg reflection waveguides.

amount of residual modal birefringence, appreciable spectral overlap exists between photons with different polarizations, if the pump wavelength is at, or close to, degeneracy. Theoretical spectra for the two cases are shown in Fig. 1(c) and (d), respectively.

Thanks to this inherent temporal and spectral indistinguishability, photons generated in a BRW are naturally entangled in polarization. A dichroic beam splitter can be used to split the biphoton into spatially distinct signal and idler paths, and the expected state is written as

$$|\Psi\rangle = \int d\omega_1 d\omega_2 \left[A_{HV}(\omega_1,\omega_2)|\omega_1,H\rangle_s|\omega_2,V\rangle_i + A_{VH}(\omega_1,\omega_2)|\omega_2,V\rangle_s|\omega_1,H\rangle_i\right] \tag{1}$$

where $A_{\alpha\beta}(\omega_1,\omega_2)$ is the probability amplitude associated with polarizations α, β (H or V) and frequencies ω_1, ω_2.

Visibility measurements and quantum state tomography were both performed to shed light on the non-classical polarization correlations between the signal and idler photons. Visibilities are shown in Fig. 1(e) and show the sinusoidal behavior associated with two-photon polarization entanglement in the "HV" and "AD" basis. Two entanglement quality indicators were computed. The concurrence was found to be 0.52, while the fidelity with the expected maximally entangled state $(|HV\rangle + |VH\rangle)/\sqrt{2}$ was computed to be 0.83. While these result show how BRW can generate on chip entanglement, off chip entanglement was also demonstrated using the same approach resulting in fidelity in excess of 0.9 [15].

The other front, where there has been progress for this technology was also reported this year in which the characteristics of an intracavity semiconductor optical parametric generator in multiple-quantum well AlGaAs/InGaAs Bragg reflection waveguide laser emitting between 986–995 nm was demonstrated. The cavity of the laser, as shown in Fig. 2, was PM for non degenerate down-conversion of pump photons to a signal between 1739–1767 nm and an idler between 2235–2328 nm. The normalized conversion efficiency was found to be $1.23 \times 10^3\%$ $W^{-1}cm^{-2}$ [16].

These results demonstrate that the BRW is inherently capable of generating polarization entanglement through current injection. Moreover, designs based on dispersion engineering show that the BRW can generate maximally-polarization-entangled photons through concurrent PM of type-0 and type-1 second order nonlinear processes [17].

2.2.2. Other Approaches

Optical pumping has also been used to generate entangled photons in semiconductor waveguides [18]. In this design, the direct generation of polarization-entangled photon pairs at room temperature and a wavelength of 1550 nm was obtained in an AlGaAs semiconductor waveguide using SPDC. The PM was achieved using counter-propagating PM scheme. The quality of the two-photon state was assessed by reconstructing the density matrix. The obtained fidelity of the Bell state was 0.83.

An electrically injected platform has been developed for quantum optical devices and experiments. This design utilizes QD that are placed in a cavity was also reported recently [19]. The design relies on a VCSEL structure which provides micropillar cavities. Such electrically injected cavities allow for the localization of vertical modes and lateral whispering gallery modes (WGM). Both types of modes are available to achieve electroluminescence through the current injection. The design aimed at electrically pumping the WGM within the micropillar to act as an in-plane laser source. This WGM laser source couples laterally to other micropillars where InGaAs QDs exist in the cavity. This design allows for WGM laser to pump the QDs such that it can guarantee that single QD emission lines interact with the cavity where the dots and the cavity operate in the weak coupling regime.

3. Outlook

While there are compelling contenders to enable the generation of entangled photons on chip at room temperature through electrical injection, this will only be the first step of many to enable a true integrated quantum optical platform, where circuits and experiments can be designed and executed. Because these sources are all realized in semiconductors, any other components such as waveguides, couplers and other devices will have to deal with the appreciable levels of photon loss and dispersion that are associated with this platform. As such the scalability of this approach will not be trivial to achieve.

The undeniable progress in the capabilities of hybrid integration on SOI has led to a few well developed active-passive integration technologies within this platform. On the other hand, there has been tremendous progress in developing optically pumped entangled photon sources, optical gates, quantum logic and numerous other building blocks for quantum optics on SOI. Given the tolerable losses and low dispersion of the dielectric materials used within this platform, it is highly likely that most of the successful, scalable quantum optical circuits developed in the near future will be associated with SOI, where pump sources will be integrated in a hybrid fashion.

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