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FrPD1 Integrated optical source of polarization entangled photons at 1310 nm
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FrPD2 Near field properties of vertical emitting laser based on 2D photonic crystal heterostructures
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FrPD3 High-Quality Factor Suspended-Wire 1D Photonic Crystal Micro-cavity in Silicon-on-Insulator
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FrPD4 InP-based Monolithic Integrated Colorless Reflective Transceiver
COBRA Research Institute, Technische Universiteit Eindhoven, Eindhoven, The Netherlands
Integrated optical source of polarization entangled photons at 1310 nm

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Abstract - We report the realization of a new polarization entangled photon-pair source based on a titanium-indiffused waveguide on periodically poled lithium niobate. The paired photons are emitted at the telecom wavelength of 1310 nm within a bandwidth of less than 1 nm. The related quantum properties are demonstrated to be of high quality.

Introduction

Quantum communication often relies on the use of single quantum systems, such as photons, to carry the quantum analog of bits, usually called qubits. To do so, individual photons merely serve as carriers and quantum information is encoded on their quantum properties, like polarization or time-bins of arrival [1]. Selecting two orthogonal states spanning the Hilbert space, for instance $|H\rangle$ and $|V\rangle$ when polarization is used, allows encoding the 0 and 1 values of the qubit, and quantum superposition makes it possible to create any state $|\psi\rangle = \alpha|0\rangle + e^{i\phi}|1\rangle$, provided the normalization rule $|\alpha|^2 + |\beta|^2 = 1$ is fulfilled. Entanglement is a generalization of the superposition principle to multiparticle systems. Polarization entangled photon-pairs can be described by states of the form

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2),$$

(1)

where the indices 1 and 2 label the two photons, respectively. The interesting property is that neither of the two qubits carries a definite value. But as soon as one of them is measured, the associated result being completely random, the other one will be found to carry the opposite value. There is no classical analog to this purely quantum feature [2].

In today's quantum communication experiments, spontaneous parametric down-conversion (SPDC) in non-linear bulk crystals is the common way to produce polarization entangled photons [3]. However, since such experiments are getting more and more complicated, they require more and more efficient sources together with narrower photon bandwidths [4, 5]. In addition, as soon as long-distance quantum communication is concerned, the paired photons have to be emitted within one of the telecom windows. The aim of this work is to gather all of the above mentioned features in a single source based on a titanium (Ti) indiffused periodically poled lithium niobate (PPLN) waveguide. We report for the first time the efficient emission of narrowband polarization entangled photons at 1310 nm, showing the best quality of two-photon quantum interference ever reported for a similar configuration [6, 7]. In the following, we will first describe the essential aspects of the source. Then, we will focus on classical characterization enabling the choice of the desired SPDC interaction. Finally, we will move on to an interferometric setup designed to evaluate the quantum quality of the source and discuss the results.

*Both authors contributed the same.
**Principle of the entangled photon-pair source**

To date, the creation of entangled photon-pairs is usually ensured by SPDC in non-linear bulk or waveguide crystals [1]. In this case, the interaction of a pump field (\(P\)) with a \(\chi^{(2)}\) non-linear medium leads, with a small probability, to the conversion of a pump photon into so-called signal (\(s\)) and idler (\(i\)) photons. Naturally, this process is subjected to conservation of energy \(\omega_p = \omega_s + \omega_i\) and momentum \(k_p = k_s + k_i + \frac{2\pi}{\lambda} \cdot \vec{u}\), where \(\lambda\) represents, in the case of a PPLN waveguide, the poling period. Note that the latter equation is also known as quasi-phase matching (QPM). In our case, we choose this condition such that, starting with a pump laser at 655 nm, we expect the generation of pairs of photons centered at the telecom wavelength of 1310 nm.

From the quantum side, since we want to generate cross-polarized entangled photons, the waveguide device has to support both vertical and horizontal polarization modes. Therefore, the well-established Ti-indiffusion technology can be applied for waveguide fabrication and a type-II SPDC process, taking advantage of the non-linear coefficient \(d_{24}\) of the material, can be used [6]. This leads, at degeneracy, to the generation of paired photons having strictly identical properties, but showing orthogonal polarizations. As depicted in Fig. 1, the paired photons are emitted simultaneously and, after filtering out the remaining pump photons, separated at a 50/50 beam splitter (BS) whose outputs are labelled \(a\) and \(b\). At this stage, when the pairs are actually separated, the two possible outputs, \(|H)\_a\rangle|V)\_b\rangle\) and \(|V)\_a\rangle|H)\_b\rangle\), have equal probabilities. Furthermore, provided the two photons are indistinguishable for any observable but the polarization, it is possible to describe them by the entangled state of equation Eq. 1. Two steps are therefore cascaded for obtaining such a state configuration, 

\[
|H)\_p\rangle \xrightarrow{NLO} \eta |H)\_a\rangle|V)\_b\rangle \xrightarrow{BS} \eta^*\frac{1}{\sqrt{Z}} (|H)\_a\rangle|V)\_b\rangle + |V)\_a\rangle|H)\_b\rangle,
\]

where \(\eta\) and \(\eta^*\) stand for the efficiencies of the non-linear process and of the entire source, respectively.

![FIG. 1: Schematic of polarization entangled photon-pair source based on an H-polarized CW laser at 655 nm pumping a titanium-indiffused PPLN waveguide; A prism (P) is used to remove the infrared light coming from the laser. The association of a high-pass filter (HPF, cut-off at 1000 nm) and a bandpass filter (BPF, 1310 nm, \(\Delta\lambda = 10 nm\)) allows removing the residual pump photons; Finally, a 50/50 beam-splitter (BS) is employed to separate the paired photons, revealing entanglement when coincidences are regarded.](image)

**Fabrication and classical characterization of the PPLN waveguide**

The required poling period for the generation of photon-pairs at the degenerate wavelength of 1310 nm was calculated to be around 6.6 \(\mu m\). Therefore, we fabricated a sample containing various waveguides widths (5, 6, and 7 \(\mu m\)) together with different poling periods (6.50 to 6.65 \(\mu m\) with a step of 0.05 \(\mu m\)). Experimentally, we got near-degeneracy photon-pair emission for a temperature of 80° in a 6 \(\mu m\)-wide waveguide for the predicted period. A fine tuning of the temperature up to 88° allowed us to get exactly both signal and idler photons at the degenerate wavelength of 1310 nm, as shown on Fig. 2. The measured bandwidth of those photons is less than 1 nm for a 3.6 cm-long sample. Note
here that the measured value of the bandwidth is very close to the resolution of our optical spectrum analyzer. The theoretical value has been estimated to be 0.6 nm which corresponds to a coherence length of about 2.8 mm.

FIG. 2: (a) Fluorescence spectra, obtained in the single photon counting regime, for various poling periods associated with a 6 μm-wide waveguide heated to 80°C when pumped at 655 nm. (b) QPM curve as function of the temperature for Λ = 6.60 μm; The degeneracy point can be reached by fine tuning of the temperature up to 88°C.

Quantum characterization of the source

Obtaining polarization entangled photon-pairs (see Eq. 1) requires these two photons to be indistinguishable for any degree of freedom, but the polarization, before they reach the beam-splitter of FIG. 1. To demonstrate the indistinguishability, we performed a non-classical two-photon interference experiment. Contrary to FIG. 1, this now consists of separating the paired photons into two spatial modes regarding their polarization state (H, V) using a polarization beam-splitter (PBS), and then recombining them at a standard fiber optic 50/50 BS. This interferometric apparatus, depicted in FIG. 3-a, permits characterizing the quantum properties of the pairs. Since photons are bosons, and provided the two photons are strictly indistinguishable, we expect them to exit the BS through the same output arm, leading to a dip in the coincidence rate, when two detectors are placed at each output. Such a destructive interference effect, first demonstrated by Hong, Ou, and Mandel (HOM) requires, in our case, to rotate one of the photon polarization states. This is ensured by the polarization controllers placed before the BS. Therefore, indistinguishability means in this case that the two photons have to show the same wavelength, bandwidth, polarization state, spatial mode, and time of arrival for obtaining a perfect overlap at the BS where the interference occurs [8]. Changing the path length difference of the two arms allows scanning over the coherence length of the single photons and leads to the so-called HOM-dip in the coincidence rate. The more indistinguishable the photons are, the better the visibility of the dip is. This figure of merit allows inferring the quality of the entangled state produced by the source (see FIG. 1 and related text).

FIG. 3-b exhibits the coincidence rate as a function of the path length difference between the two arms and shows the obtained HOM interference while single photon detection remains constant in both APDs. In our case, the associated net visibility and FWHM are of about 84% and 1.5 mm, respectively. Work is in progress towards understanding the origin of the reduction of visibility. Energy-time entanglement or other phase-matched
interactions, such as Cerenkov, in our non-linear waveguide can be seen as sources of visibility degradation. In any case, the obtained visibility is, to our knowledge, the best ever reported in a similar configuration, i.e. cross-polarized photons at telecom wavelength generated by a Ti-indiffused PPLN waveguide. This is also a clear signature that a high quality of entanglement can be expected from the setup of Fig. 1.

Conclusion

Using a type-II PPLN waveguide, we have demonstrated a narrowband and bright source of cross-polarized paired photons since we estimated the production rate to be on the order of $10^5 / s/ GHz/mW$, which is one of the best ever reported in such a configuration [6, 7]. Using a HOM-type setup, we obtained an anti-coincidence visibility of 84% indicating a good level of photon indistinguishability. These preliminary results permits expecting our source to be an efficient, compact, and reliable key element providing narrow and high-quality polarization entangled photon-pairs for the first time at 1310 nm. Finally, this work clearly highlights the potential of integrated optics for long-distance quantum communication protocols.

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Near field properties of vertical emitting laser based on 2D photonic crystal heterostructures

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Abstract. Vertical emitting μlasers based on 2D photonic crystal heterostructures constituted by a square lattice of μpillars bonded on a vertical Bragg mirror have been realized at 1.5μm. Near field properties show the slow Bloch mode confinement inside the heterostructure.

1. Introduction

2D photonic crystal properties, especially at band edges of the dispersion curves where the group velocity tends to zero, allow a wide range of micro-photonic devices that require slow light. To achieve vertical emission, Slow Bloch Modes (SBM) located above the light line are of great interest. Indeed, they have the ability to couple with free space modes. Especially at Γ-point of the dispersion characteristic, strong lateral confinement is expected and very compact structures can be designed. It is thus possible to finely tune the temporal (quality factor) and spatial (SBM confinement and emission characteristic) properties of SBM located at Γ-point to achieve low threshold vertical emitting μlasers.

Based on the concept we developed in ref [1], we fabricated and characterized 2D PC photonic heterostructures constituted by a square lattice of Indium Phosphide (InP) pillars bonded on a Si/SiO2 Bragg mirror. Particularly, we study the near field properties of the first SBM located at Γ-point.

![Figure 1. 2D band diagram of a square lattice of dielectric pillars for two InP filling factor: 0.4 and 0.5 in TE polarization. The SBM of interest is circled.](image)

2. Sample design and fabrication

We focused on the first Γ-point SBM in a square lattice of Indium Phosphide (InP) pillars, as shown in the band diagram of the Fig. 1. This mode does not couple to free space modes for symmetry reasons [2] and exhibits a very flat band curvature. 3D FDTD calculations show that quality factors around 1500 can be achieved at 1.5μm in a 21x21 pillar lattice having period of 0.7μm and filling factor of 50%. To increase the quality factor of this SBM without increasing the mode volume, we use a photonic heterostructure as defined in [1]. The heterostructure principle is to slightly increase the radius of the outer pillars to
inhibit the lateral leakages leading to a strong lateral photon confinement. Indeed, by increasing the InP filling factor of the outer rows, we create a barrier for the photons located inside the cavity (see band diagram in figure 1).

The studied heterostructure consists of an inner 11x11 pillar cavity having a filling factor (ff) of 50% surrounded by 5 rows with ff=51.6% and same period, which yields to a difference between the pillar radii of the cavity and the barrier of 5nm. The quality factor of the SBM in the heterostructure calculated using 3D FDTD is thus 3000 whereas it reaches a few hundreds without any row. The photon lifetime is then only limited by vertical losses. These losses can however be reduced by associating the 2D PC heterostructure with a vertical Bragg mirror, as depicted in figure 2. The silica gap between the 2D PC and the Bragg mirror is 790nm which yields to a significantly increase of the quality factor [3]. Quality factors as high as 10000 can then be reached.

The device was fabricated by patterning an InP membrane containing 4 InAsP quantum wells bonded on a silicon/silica Bragg mirror using e-beam lithography and reactive ion etching (RIE). SEM images of the fabricated structures are shown in figure 2.

We fabricated uniform 2D PC as well as heterostructures to compare the two PC structures and their efficiency in terms of laser threshold and field confinement. The uniform PC structures are constituted by 30x30 pillars (≈5x25μm). For the heterostructure, the cavity is constituted by 10x10 pillars (≈8x8μm) surrounded by 5 rows having a slightly higher pillar radius.

![Figure 2. a) Studied heterostructure associated with a Si/SiO2 Bragg mirror. B) SEM images of the fabricated 2D PC.](image)

3. Photoluminescence properties

The samples are first characterized at room temperature by photoluminescence using a pulsed laser diode emitting at 800nm as optical pump. The duty cycle is 1.7% and the pulse width is 6ns. The pulsed diode is focused under normal incidence on the structures using an achromatic objective (numerical aperture of 0.4) onto a surface of around 10μm in diameter. The emitted PL signal by the structure is then collected through the same objective lens and analyzed by a monochromator and a cooled InGaAs photodetector array.

We obtained laser emission for a uniform 2D PC and a 2D PC heterostructure around 1.5μm. Figures 3 a and 3 b shows the Light-in/Light-out curves for each kind of structures. The laser threshold for the uniform structure is about 8mW in terms of peak pump power which is of the order of the obtained threshold for a 2D PC structure constituted by a hole graphite lattice bonded on the same Bragg mirror with the same silica gap between the 2D PC and the Bragg mirror [3]. The laser threshold for the heterostructure is about 12.5mW.
The filling factor of the cavity and the barrier are very close to each other. This is almost indistinguishable using SEM observations. A way to know precisely if the confinement of the SBM is achieved inside the heterostructure is to use near field scanning optical microscopy (NSOM) [4]. Indeed, using NSOM characterizations we can access directly to the field distribution inside the 2D PC that is the evanescent components of the SBM which is impossible with a far field experimental set-up. This will give a clear insight into the PL structuration of the SBM inside the PC cavity and the SBM confinement due to the heterostructure.

4. Near field characterizations

In the NSOM experimental set up, the pump beam, which is the same pulsed laser diode as in the far field experiment, is focused on the structure with an objective lens. The PL signal is collected in the near field of the structure (<20nm) by an uncoated, chemically etched optical silica fiber tip. Thus, the near field probe does not perturb notably the SBM spatial distribution. The signal is then guided to a monochromator and detected by a cooled InGaAs photodetector array. The distance between the near field probe and the sample is controlled by a shear force feedback. In this configuration, topographic images as well as PL images can be recorded at the same time.

Figure 4 a shows the topography of a uniform 2D PC constituted by a square lattice of pillars. The near field PL map recorded simultaneously to figure 4 a at 1517nm is given in figure 4 b. Figure 5 presents the near field distribution in the 2D PC heterostructure studied in section 3. The SBM confinement inside the heterostructure is clearly visible. In the case of the uniform 2D PC the field leaks laterally as expected from 3D FDTD calculations [2]. NSOM characterizations demonstrate the confinement of a SBM located above the light cone.
4. Conclusion

We fabricated and characterized vertical emitting lasers at 1.5\mu m and at room temperature constituted by 2D PC structures bonded on a silicon/silica Bragg mirror. Laser emission is achieved in a uniform 2D PC as well as in a PC heterostructure. In a 2D heterostructure, the SBM is laterally confined inside the cavity. Near field optical microscopy allowed us to demonstrate experimentally the SBM confinement by mapping the spatial distribution of the intensity in the evanescent tail of the field, at 20nm above the PC slab.

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References


High-Quality Factor Suspended-Wire 1D Photonic Crystal Micro-cavity in Silicon-on-Insulator

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Abstract. We present a comparison of high Q-factor tapered membrane-type one-dimensional photonic crystal micro-cavities embedded in photonic wire waveguides based on silicon-on-insulator (SOI). Q-factor values as large as 24,000 have been measured, together with normalized transmission of 67%: an improvement in the Q-factor value in comparison with previous results obtained on structures with silicon cores supported by a silica buffer layer. Simulation using a 3D FDTD approach shows close agreement with measurements.

Introduction

High quality factor waveguide micro-cavity structures have been a topic of research interest for several years. Hole-based one-dimensional photonic crystal (PhC) micro-cavities embedded in photonic wire waveguides, with a Q-factor value of around 500, were described in [1]. We now report achievement of an experimental Q-factor value as large as 24,000 in an air-suspended photonic-wire waveguide micro-cavity structure - a value that is, to our knowledge, the highest achieved in this particular format.

High Q-factor values have been reported for several different device designs [2,3], but the requirement of achieving high Q-factor values, together with large optical transmission and small modal volumes, has become increasingly important [4]. Recent work based on photonic-wires combined with 1D PhC micro-cavities having silicon waveguide cores supported by a silica buffer layer has achieved Q-factor values in excess of 100,000. Air-suspended membrane-type photonic crystal structures [5], including micro-cavities, have been successfully fabricated and have demonstrated very high cavity Q-factor values, but there are still issues of mechanical stability, robustness and fabrication complexity. The motivation of our work on designing and producing suspended-membrane PhC/PhW waveguide microcavities has been to investigate the impact of increased optical confinement within the waveguides, as well as the effect of possible reductions in the propagation losses.

Design considerations and FDTD simulation approach

Planar one-dimensional photonic crystal micro-cavities embedded in 500 nm wide photonic wire waveguides have been realized recently with Q-factor values of approximately 18,500 - and normalized transmission of nearly 85% [4]. This performance combination was achieved in structures in which the silicon guiding layer was supported by a silica lower cladding or buffer layer. The devices produced are useful for telecommunications applications such as dense wavelength division multiplexing (DWDM) and optical signal processing more generally. Detailed descriptions of the devices can be found in reference [4]. Figure 1 shows an SEM image...
of a particular device in which the silica cladding underneath the silicon core has been removed - creating an air-bridge type of structure (see the inset in Fig. 1).

![Inset figure](image)

*Figure 1: SEM image of an air bridge type of tapered single-row PhC/PhW waveguide with cavity length, c, four hole tapers within the cavity - and two hole tapers outside the cavity. Inset is a bird's eye view (angle ~ 25°) of the suspended PhC/PhW micro-cavities.*

The structure consists of two mirrors with four period hole structures separated by a micro-cavity spacer section. Four-hole and two-hole aperiodic tapered structures were inserted within and outside the cavity on each mirror to reduce the modal mismatch between the un-patterned photonic-wire sections and the periodic hole mirror sections. 3D FDTD simulations have been carried out on similar device structures in reference [4] - but with the silica buffer layer having been removed. This device has an N = 4 periodic mirror with hole diameters of 182 nm and periodic spacing between the holes of 350 nm.

![Graph](image)

*Figure 2: 3D FDTD computed for tapered one-dimensional PhC/PhW micro-cavities embedded in 500 nm photonic wire waveguides with cavity length, c ~ 425 nm for suspended wire (red line) and without removal of the silica buffer lower-cladding layer (black line).*
Figure 2 shows a comparison of the transmission spectra for tapered photonic crystal micro-cavities embedded in 500 nm photonic wire waveguides obtained using the 3D finite-difference time-domain (FDTD) approach for both suspended wire structures and ones supported by a silica buffer layer. Our comparison is based on structures in which all of the parameters for the patterning of the silicon waveguide core are the same, i.e. wire width, hole diameters and spacings. The simulations show an increase in the Q-factor value from 17,500 to 34,000 for the suspended wire, in comparison with the value for the structure in which the silica buffer layer remains below the silicon guiding layer. A shift in the resonance frequency, in going from the supported structure to the suspended structure, by approximately -3 nm was also measured for this design arrangement - together with an increase in optical transmission by almost 10%. The shift is due, in particular, to a reduction in the effective refractive index of the guided light - thus shifting the resonance towards a shorter wavelength when the silica support layer is removed.

**Experimental results**

The devices were fabricated using direct-write electron-beam lithography on a Vistec VB6 machine, together with reactive ion-etching. They were characterized using a tunable laser covering the range from 1457 nm to 1580 nm. The TE polarized light was end-fire coupled into and out of the waveguides and was detected using a germanium photo-detector.

![Figure 3: Measurement result for suspended PhC/PhW micro-cavities in a suspended wires with cavity lengths, c (a) 390 nm (b) 415 nm (c) 440 nm (d) 465 nm](image)

Experimental results corresponding to the simulation results obtained using the 3D FDTD approach given in Fig. 2 are shown in Fig. 3. The best experimental Q-factor value - approximately 24 000 - was obtained for a cavity length, c, of 390 nm and at a normalized transmission level of 65%.
With silica buffer Suspended wire Normalized Normalized cladding waveguides length, \(c/\text{nm}\) \(Q\) \(\text{Transmissio} \ n\) \(Q\) \(\text{Transmissio} \ n\)
\begin{tabular}{llllll}
390 & 18 & 500 & 0.85 & 24 & 000 & 0.67 \\
415 & 16 & 600 & 0.82 & 16 & 700 & 0.71 \\
440 & 9 & 000 & 0.71 & 7 & 200 & 0.45 \\
465 & 5 & 900 & 0.83 & 2 & 000 & 0.58 \\
\end{tabular}

Table 1: Comparison of the measured results for the suspended wire waveguides and the one with silica cladding still exist underneath the wire waveguides

As the cavity length was increased from 390 nm to 465 nm, the Q-value decreased to 2000, together with a reduction in the normalized optical transmission level. Table 1 gives the results for the structures shown in Fig 1, in comparison with our previous results – obtained without removal of the silica buffer layer.

Conclusions

We have successfully demonstrated a further enhancement of the PhC/PhW cavity Q-factor value, from 18,500 to approximately 24,000, using the membrane type of structure - at a cavity length of 390 nm - for one of our design arrangements. This value is somewhat lower than the value of 34,000 predicted in the corresponding simulation. Discrepancies between simulation and measurement are probably attributable to imperfections in the fabrication processes. We believe that high Q-factor values, possibly up to more than 500,000, will be achievable if the correct combination of the number of periodic mirror holes, cavity length and aperiodic hole tapering within and outside the cavity is used. The enhancement in the Q-value in this particular design is due to the increase in the optical confinement – thus enhancing the field intensity of the mode confined within the micro-cavity. The effective refractive index changes due to the air gap underneath the silicon guiding layer have also produced a shift in the resonance frequency by approximately 3 nm. The 3D FDTD approach used to simulate the devices has shown reasonably close agreement with the measured results.

References

InP-based Monolithic Integrated Colorless Reflective Transceiver


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A colorless monolithic integrated transceiver based on InP is presented. This transceiver consists of a wavelength duplexer, a reflective SOA (RSOA), and a short photodetector, suitable for the application at the user side to download and upload information carried by two different wavelengths spaced 200 GHz near 1.55 μm. The reflective SOA is 750 μm long, offers 5 dB fiber-to-fiber gain, and 1 Gbit/s dynamic operation at different wavelengths after wire bonding. The integrated 60 μm long photodetector shows 0.25 A/W external responsivity and up to 14 GHz 3 dB bandwidth after wire bonding.

Introduction

With the ever-increasing demands on the data rate at the user side to exchange information, fiber-to-the-home (FTTH) has been shown to be one of the most promising solutions. Currently the maximum widely available bitrate of installed optical network units (ONU) at the user side is 156 Mbit/s for upstream data carried by 1310 nm Fabry-Pérot laser, and 656 Mbit/s downstream data carried by 1550 nm in a TDM-BPON system in Japan [1]. This system uses wavelength-specific optical transceivers which will finally hinder the large-scale deployment of FTTH system due to cost and difficulty in maintenance. A colorless transceiver may be a more cost-effective and flexible alternative. A number of groups have demonstrated colorless upstream operation up to 1 Gbit/s with different methods, such as self-seeding, injection locking, spectral seeding or laser injected reflective SOA [2, 3, 4, 5]. However, most demonstrations were realized with discrete commercial components, which are costly and not practical in the user access network.

In this paper, a monolithic integrated colorless transceiver based on butt-joint active-passive regrowth on InP is presented, and it is one of the key devices developed for Broadband Photonics Architecture [6]. It consists of a wavelength duplexer, a reflective SOA, and a photodetector, Fig. 1. The device works as follows. Two wavelengths (λ1 and λ2) come from the network into the transceiver from the left side. They are spatially separated by the wavelength duplexer and guided to the photodetector (λ1) and to the reflective SOA modulator (λ2). The downstream data, carried by λ1, is detected by the photodetector, while λ2 is a continuous wave (CW) light and is guided to the RSOA where it is modulated, amplified and reflected back to the network.

The wavelength duplexer is a Mach-Zehnder (MZ) interferometer, composed of a 1 × 2 and a 2 × 2 3-dB MMI splitter/combiner, connected by two waveguides with different lengths. Due to the large 3-dB optical gain bandwidth of the SOA, it can be operated in a large wavelength range for a colorless operation by modulating the electrical current. A high reflectivity coating (HR) is applied at the SOA side of the chip, causing the light
to be reflected back. The SOA is shallowly etched, 2 μm wide and 750 μm long. The photodetector is shallowly etched, 2 μm wide and 60 μm long. To avoid lasing and to reduce the coupling loss, the facet of the chip where the light is coupled into and out of the device, is provided with an anti-reflection coating (AR). To further reduce any residual reflections, the input waveguide is placed at an angle of 7° toward the chip facet [7], and a mode filter is inserted to suppress propagation of the first-order mode.

Fabrication

The device was fabricated in material grown on an N-type InP substrate by three-step low pressure metal-organic-vapor-phase epitaxy (MOVPE). The first epitaxy finished with a 120 nm thick SOA active InGaAsP layer (Q1.55, λgap = 1.55 μm), embedded between two quaternary confinement layers (Q1.25) with different doping levels, covered by a 200 nm thick p-InP layer. Next, the active sections were defined by lithography and reactive ion etching (RIE) using a SiNx layer as etching mask. In the second epitaxy step, a Q1.25 InGaAsP layer was selectively grown for the passive sections with the SiNx mask protecting the active sections[8]. In the third epitaxy step, the p-doped InP cladding layers with graded doping level and the p-InGaAs contact layer were grown with a total thickness of 1300 nm, Fig. 2. All the waveguides were fabricated by reactive ion etching (RIE). Polyimide was spun for passivation and planarization. By etching back the polyimide, the p-InGaAs contact layer was exposed and Ti/Pt/Au metal layers were evaporated to form the electrodes on the top and the ground (n-InP) at the backside. To improve the conductivity, the device was annealed at 325°C for 30 seconds, and electro-plated with gold. The HR coated facet has about 90% reflectivity, and AR coated facet has about 0.1% reflectivity. The device was glued and wire bonded on a AIN RF submount with coplanar waveguide design, Fig. 3, to enable measurements with a GSG RF probe. The measured 3-dB bandwidth for such a RF submount is more than 20 GHz. The bonded wire has 20 μm radius, and is approximately 2 mm long. During the characterization, the chip was stabilized on a copper chuck and cooled by a Peltier element.
Figure 3: Bonded chip on a AlN RF submount (left) and bonded RSOA and the photodetector (right).

Figure 4: 1 Gbit/s eye diagram at $\lambda = 1541.9\,\text{nm}$ with input optical power $P_{\text{in}} = -11\,\text{dBm}$, 80 mA injection current and 0.78 V modulation depth.

Figure 5: The measured frequency response of the wire bonded photodetector at $-6\,\text{V}$ when $P_{\text{in}} = -20\,\text{dBm}$.

**Characterisation**

The reflective SOA is operated by modulating the electrical current. Because of residual reflections, the RSOA of the bonded device starts to lase at an injection current of 110 mA. The device gain peak is near 1530 nm, and the RSOA achieved about 5 dB fiber-to-fiber gain when injecting 100 mA. This fiber-to-fiber gain can be increased by reducing the fiber-chip coupling loss, which in our case is around $2 \times 5\,\text{dB}$. To measure the bitrate of the SOA, we use a pulse pattern generator to produce 1 GHz PRBS code with $2^{31} - 1$ word length. The bias current was set at 80 mA, the modulation amplitude is 0.78 V over $50\,\Omega$ impedance. The input optical power is $-11\,\text{dBm}$, and the recorded eye-diagram is presented in Fig. 4, showing a quality factor of 9, and an extinction ratio of 5.2 dB. The measurement has been done on four different upstream wavelengths from 1532.3 nm to 1541.9 nm, and the results are similar.

The photodetector was characterized by performing on-wafer S-parameter measurements in the range of 130 MHz to 20 GHz with a lightwave component analyzer HP8703A and a 50 GHz RF-probe. The photodetector was biased at $-6\,\text{V}$ through a 65 GHz bias tee,
and the injected wavelengths are 1536 nm and 1545.56 nm with −20 dBm optical power before fiber chip coupling. The measured small signal frequency response is given in Fig. 5. The measured 3 dB frequency response is 14 GHz for a 60 μm long wire bonded photodetector, and the external responsivity shown in Fig. 5 includes the extra loss from the polarization controller and two fiber connectors. The measured static photoresponsivity is up to 0.25 A/W over a large wavelength range, which corresponds to about 64% on chip quantum efficiency (including the loss of the wavelength duplexer) when the chip fiber coupling loss is taken as −5 dB.

**Conclusion**

We presented a monolithic integrated transceiver that operates up to 1 Gbit/s for upstream data (modulated RSOA) and around 14 Gbit/s for downstream data (reversely biased photodetector). The reflective SOA offers up to 5 dB fiber-to-fiber gain for 100 mA bias current at 1532.3 nm, which is mostly limited by the fiber-chip coupling efficiency. The bonded photodetector has a high external responsivity up to 0.25 A/W within large wavelength range.

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**References**


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