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InAs/InP(100) quantum dot waveguide photodetectors for swept-source optical coherence tomography around 1.7 µm

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Abstract: In this paper a study of waveguide photodetectors based on InAs/InP(100) quantum dot (QD) active material are presented for the first time. These detectors are fabricated using the layer stack of semiconductor optical amplifiers (SOAs) and are compatible with the active-passive integration technology. We investigated dark current, responsivity as well as spectral response and bandwidth of the detectors. It is demonstrated that the devices meet the requirements for swept-source optical coherent tomography (SS-OCT) around 1.7 µm. A rate equation model for QD-SOAs was modified and applied to the results to understand the dynamics of the devices. The model showed a good match to the measurements in the 1.6 to 1.8 µm wavelength range by fitting only one of the carrier escape rates. An equivalent circuit model was used to determine the capacitances which dominated the electrical bandwidth.

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References and links

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, “Optical coherence tomography,” Science 254(5035), 1178–1181 (1991).
2. S. R. Chinn, E. A. Swanson, and J. G. Fujimoto, “Optical coherence tomography using a frequency-tunable optical source,” Opt. Lett. 22(5), 340–342 (1997).
3. M. Choma, M. Sarunic, C. Yang, and J. Izatt, “Sensitivity advantage of swept source and Fourier domain optical coherence tomography,” Opt. Express 11(18), 2183–2189 (2003).
4. B. Potsaid, I. Gorczynska, V. J. Srinivasan, Y. Chen, J. Jiang, A. Cable, and J. G. Fujimoto, “Ultra-high speed spectral / Fourier domain OCT ophthalmic imaging at 70,000 to 312,500 axial scans per second,” Opt. Express 16(10), 15149–15169 (2008).
5. J. G. Fujimoto, M. E. Brezinski, G. J. Tearney, S. A. Boppart, B. Bouma, M. R. Hee, J. F. Southern, and E. A. Swanson, “Optical biopsy and imaging using optical coherence tomography,” Nat. Med. 1(9), 970–972 (1995).
6. D.-J. Faber, Department of Biomedical Engineering and Physics, Academic Medical Center (AMC), Meibergdreef 9, 1105 AZ Amsterdam, The Netherlands (personal communication, 2007).
7. V. M. Kodach, J. Kalkman, D. J. Faber, and T. G. van Leeuwen, “Quantitative comparison of the OCT imaging depth at 1300 nm and 1600 nm,” Biomed. Opt. Express 1(1), 176–185 (2010).
8. B. W. Tilma, Y. Jiao, J. Kotani, B. Smalbrugge, H. P. M. M. Ambrosius, P. J. Thijss, X. J. M. Leijtens, R. Nötzel, M. K. Smit, and E. A. J. M. Bente, “Integrated tunable quantum-dot laser for optical coherence tomography in the 1.7 µm wavelength region,” IEEE J. Quantum Electron. (to be published).
9. D. J. Faber and T. G. v. Leeuwen, “Optical coherence tomography,” in Optical-thermal response of laser-irradiated tissue, 2nd ed., A. J. Welch and M. J. C. v. Gemert, eds. (Springer, 2011).
10. Tholfrabs PDB120 series, http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=2151.
11. I. Kimakin, N. Biyikli, B. Butun, O. Aytur, S. M. Unlu, and E. Ozbay, “InGaAs-based high-performance p-i-n photodiodes,” IEEE Photon. Technol. Lett. 14(3), 366–368 (2002).
12. H. G. Bach, A. Beling, G. G. Mekonnen, R. Kunkel, D. Schmidt, W. Ebert, A. Seeger, M. Stollberg, and W. Schlack, “InP-based waveguide-integrated photodetector with 100-GHz bandwidth,” IEEE J. Sel. Top. Quantum Electron. 10(4), 668–672 (2004).

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13. Y. Zhang, Y. Gu, C. Zhu, G. Hao, A. Li, and T. Liu, “Gas source MBE grown wavelength extended 2.2 and 2.5 μm InGaAs PIN photodetectors,” Infrared Phys. Technol. 47(3), 257–262 (2006).
14. J. Oh, S. Cusak, and C. Campbell, “High-speed interdigitated Ge PIN photodetectors,” IEEE Photon. Technol. Lett. 14(3), 369–371 (2002).
15. A. Rogalski and R. Ciupa, “Performance limitation of short wavelength infrared InGaAs and HgCdTe photodiodes,” J. Electron. Mater. 28(6), 630–636 (1999).
16. Thorlabs SIR5 series, http://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=1297.
17. Hamamatsu G8423 series, http://sales.hamamatsu.com/index.php?id=13157898.
18. Thorlabs FDG series, http://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=2822.
19. Hamamatsu P series, http://jp.hamamatsu.com/products/sensor-ssd/pd128/pd134/index_en.html.
20. C. Zinoni, B. Altung, L. H. Li, F. Marsili, A. Fiore, L. Lunghe, A. Gerardino, Y. B. Vakhitov, K. V. Smirnov, and G. N. Gol’tsman, “Single-photon experiments at telecommunication wavelengths using nanowire superconducting detectors,” Appl. Phys. Lett. 91(3), 031106 (2007).
21. S. Kim, H. Mohseni, M. Erdtmann, E. Michel, C. Jelen, and M. Razeghi, “Growth and characterization of InGaAs/InGaP quantum dots for midinfrared photoconductive detector,” Appl. Phys. Lett. 73(7), 963–965 (1998).
22. S. F. Tang, S.-Y. Lin, and S.-C. Lee, “Near-room-temperature operation of an InAs/GaAs quantum-dot infrared photodetector,” Appl. Phys. Lett. 78(17), 2428–2430 (2001).
23. B. W. Tilma, M. S. Tahvili, J. Kotani, R. Notzel, M. K. Smit, and E. A. J. M. Bente, “Measurement and analysis of optical gain spectra in 1.6 to 1.8 μm InAs/InP (100) quantum-dot amplifiers,” Opt. Quantum Electron. 41(10), 735–749 (2009).
24. S. Anantathanasarn, R. Notzel, P. J. van Veldhoven, F. W. M. van Otten, Y. Barbarin, G. Servanton, T. de Vries, E. Smalbrugge, E. J. Geluk, T. J. Eijkemans, E. A. J. M. Bente, Y. S. Oei, M. K. Smit, and J. H. Wolter, “Lasing of wavelength-tunable InAs/InGaAs quantum-dot lasers grown by metal organic vapor-phase epitaxy,” Appl. Phys. Lett. 89(7), 073115 (2006).
25. R. Notzel, S. Anantathanasarn, R. P. J. van Veldhoven, F. W. M. van Otten, T. J. Eijkemans, A. Trampert, B. Satpati, Y. Barbarin, E. A. J. M. Bente, Y.-S. Oei, T. de Vries, E.-J. Geluk, B. Smalbrugge, M. K. Smit, and J. H. Wolter, “Self assembled InAs/InP quantum dots for telecom applications in the 1.55 μm wavelength range: wavelength tuning, stacking, polarization control, and lasing,” Jpn. J. Appl. Phys. 45(8B), 6544–6549 (2006).
26. H. Wang, J. Yuan, P. J. van Veldhoven, T. de Vries, B. Smalbrugge, E. J. Geluk, E. A. J. Bente, Y. S. Oei, M. K. Smit, S. Anantathanasarn, and R. Notzel, “Butt joint integrated extended cavity InAs/InP (100) quantum dot laser emitting around 1.55 μm,” Electron. Lett. 44(8), 522–523 (2008).
27. UltraFast Sensors, http://www.ultrafastsensors.com/Amplifier.htm.
28. Y. C. Xin, Y. Li, A. Martinez, T. J. Rotter, H. Su, L. Zhang, A. L. Gray, S. Luong, K. Sun, Z. Zou, J. Zilko, P. M. Varangis, and L. F. Lester, “Optical gain and absorption of quantum dots measured using an alternative segmented contact method,” IEEE J. Quantum Electron. 42(7), 725–732 (2006).
29. L. Yang, D. Dai, B. Yang, Z. Zheng, and S. He, “Characteristic analysis of tapered lens fibers for light focusing and butt-coupling to a silicon rib waveguide,” Appl. Opt. 48(4), 672–678 (2009).
30. A. A. Ukhanov, R. H. Wang, T. J. Rotter, A. Stintz, L. F. Lester, P. G. Eliseev, and K. J. Malloy, “Orientation dependence of the optical properties in InAs quantum-dash lasers on InP,” Appl. Phys. Lett. 81(6), 981–983 (2002).
31. L. Xu, M. Nikoufard, X. Leijtens, T. de Vries, E. Smalbrugge, R. Notzel, Y. Oei, and M. K. Smit, “High-performance InP-based photodetector in an amplifier layer stack on semi-insulating substrate,” IEEE Photon. Technol. Lett. 20(23), 1941–1943 (2008).
32. K. Kato, S. Hata, K. Kawanou, J. Yoshiida, and A. Kozen, “A high-efficiency 50 GHz InGaAs multimode waveguide photodetector,” IEEE J. Quantum Electron. 28(12), 2728–2735 (1992).
33. M. Sugawara, K. Mukai, Y. Nakata, H. Ishikawa, and A. Sakamoto, “Effect of homogeneous broadening of optical gain on lasing spectra in self-assembled InGaAs/AsGaAs quantum dot lasers,” Phys. Rev. B 61(11), 7595–7603 (2000).
34. M. Gioannini, A. Sevega, and I. Montrosset, “Simulations of differential gain and linewidth enhancement factor of quantum dot semiconductor lasers,” Opt. Quantum Electron. 38(4-6), 381–394 (2006).
35. H. Jiang and P. K. L. Yu, “Equivalent circuit analysis of harmonic distortions in photodiode,” IEEE Photon. Technol. Lett. 10(11), 1608–1610 (1998).
36. J. Kotani, P. J. van Veldhoven, T. de Vries, B. Smalbrugge, E. A. J. M. Bente, M. K. Smit, and R. Notzel, “First demonstration of single-layer InAs/InP(100) quantum-dot laser: continuous wave, room temperature, ground state,” Electron. Lett. 45(25), 1317–1318 (2009).
37. E. W. Bogart, R. Nötzel, Q. Gong, J. E. M. Haverkort, and J. H. Wolter, “Ultrafast carrier capture at room temperature in InAs/InP quantum dots emitting in the 1.55 μm wavelength region,” Appl. Phys. Lett. 86(17), 173109 (2005).
38. M. Gioannini and I. Montrosset, “Numerical analysis of the frequency chirp in quantum-dot semiconductor lasers,” IEEE J. Quantum Electron. 43(10), 941–949 (2007).
1. Introduction

Since its first proposal and demonstration [1], optical coherence tomography (OCT) has been proven to be an excellent solution for in vivo medical imaging without physical contact. It shows large potential in a wide range of applications such as ophthalmology, intravascular imaging, dermatology, and developmental biology. The swept-source OCT (SS-OCT) is one of the more successful techniques among other OCT schemes. In SS-OCT, the image along the depth of the sample to be investigated (e.g., tissue) is reconstructed by measuring a spectrally resolved interferometer signal [2] using a swept narrow-band laser source. The interferometer is Michelson type where the reference arm length is fixed and the second arm is lead to the sample. The reflected lights from the two arms are combined and will interfere. As the laser source sweeps its frequency, the intensity of the output of the interferometer is detected by a photodetector, the signal from which is recorded in real time. The information of reflections along the depth of the sample is then extracted by performing a Fourier transform of the recorded interference signal. The SS-OCT offers several advantages over other types of OCT systems, e.g., higher sensitivity [3], lower sensitivity roll-off with imaging depth [4] and a more simple optical design.

The dominating limitation of imaging depth of SS-OCT in biological samples is the intensity reduction of the reflected light as the depth increases. In the wavelength regions that are currently used, this signal fading with depth is dominated by scattering of light in the sample and less so by the absorption [5]. One way to reduce scattering is to use longer wavelengths compared to the more commonly used 0.8 µm or 1.3 µm wavelength regions. The wavelength range from 1.6 to 1.8 µm lies in between two strong water absorption peaks and the scattering should be reduced even more. An improvement of imaging depth of up to 80% in the sample is predicted [6] with respect to the 1.2 to 1.3 µm range. An improvement in imaging depth of up to 40% was demonstrated in [7] for OCT in the 1.5 to 1.7 µm range. This was despite the fact that the water absorption at 1.5 µm is still significant.

Two main components are required to open up OCT imaging in an SS-OCT system in this long wavelength range. The first is a swept laser source. In previous work [8], we have developed an experimental monolithically integrated tunable laser around the 1.7 µm wavelength region for the SS-OCT application. It is integrated on a single InP chip and uses InAs/InP(100) quantum dots (QDs) for its optical amplifiers. The laser can achieve a tuning range of 60 nm and a scanning speed of 0.5 kHz. The output power of the laser was however limited (0.1 mW) and measurements could only be done in a free-space Michelson interferometer setup. Even the measurements on this set-up were seriously hampered by the commercial photodetector either by the high noise-level of spectrally optimized detector or by the limited spectral range of a standard low noise detector optimized for 1.55 µm. In both cases the signal-to-noise ratio (SNR) deteriorates to such an extent as to wipe out any advantage expected by the use of the long wavelengths through the reduced scattering in the sample. A suitable photodetector is thus the second main component that is essential to realize the potential for OCT imaging in the 1.6 to 1.8 µm range. Such detectors are not readily available commercially. The limited spectral range of the detector used in [7] was the reason for limiting the studies to the less suitable 1.5 to 1.7 µm range.

In this paper we demonstrate that InAs/InP(100) QD waveguide photodetectors meet all the requirements for application in an OCT system operating in the 1.6 to 1.8 µm wavelength range that can achieve an improved imaging depth. These photodetectors thus open up the long wavelength region for OCT imaging. The technology of the integrated tunable QD laser discussed above allows for the monolithic integration of components of the interferometer with the laser. In particular the detector can be integrated provided that the QD active structure used for the detectors is compatible with the laser. Thus the detector could then be fabricated in the same process as the laser and be fully integrated with the laser. This is the
main advantage of the QD active material and motivation for the investigation presented in this paper.

In order to maximize the performance of the OCT system, the photodetectors should have a high responsivity, preferably higher than 0.5 A/W over the whole wavelength range around 1.7 µm where the quantum limit is 1.37 A/W. A high responsivity is the first condition to obtain a high extinction ratio (ER) of the beating signal, thus improving the SNR of the images. A flat spectral response is also preferable to ensure the efficient use of the entire wavelength range of the swept laser and to obtain the highest spatial resolution. To match the state-of-the-art 10 µm resolution in tissue, the 1.7 µm OCT systems require at least a bandwidth of 100 nm [9]. The dark current of the photodetectors should be low at room temperature. The level of the dark current will limit the minimum detectable optical power and thus maximum imaging depth. The noise level of typical commercial photodetectors used for OCT application [10] is associated with a dark current of the photodetectors of around 30 nA maximum. Thus we choose the maximum tolerable dark current as 30 nA. The signal bandwidth of the photodetectors must be sufficient for 3D SS-OCT imaging where the requirement of the repetition rate is the highest. For a swept laser source with a scanning speed of 20 kHz and 4000 wavelength samples in each scan, the minimum bandwidth of the photodetectors should be approximately 200 MHz (e.g., a 3D image of 200 by 200 pixels could then be recorded in approximately 2 s). We believe a laser with 20 kHz rate is feasible in the technology of the integrated laser system which we have demonstrated. Therefore we consider a bandwidth of 200 MHz to be sufficient. Since most of the proposed OCT realisations are based on fiber systems, the detector should be fiber coupled. Thus a waveguide photodetector is promising among other types of detectors.

Several semiconductor material systems can be used in principle for photodetectors working in the 1.6 to 1.8 µm wavelength range. Photodetectors based on InGaAs, shortwave-infrared (SWIR) InGaAs, Ge, PbS or HgCdTe have been studied intensely [11–15] and are commercially available [16–19]. But they have limitations on the performance such as low responsivity, high wavelength dependency of the spectral response, high dark current or high complexity of cooling. Work on QD photodetectors reported in literature focus on single photon detection [20]. Such devices are typically operated at cryogenic temperatures. QD photodetectors have also been developed in the mid-infrared wavelength region [21,22]. But the responsivities of them are low (~0.1 A/W at peak wavelength) thus not suitable for OCT application. To our knowledge this is the first publication on QD photodetectors in the 1.6 to 1.8 µm wavelength range.

In this paper, we present InAs/InP(100) QD waveguide photodetectors sensitive in the 1.6 to 1.8 µm wavelength range. These devices have advantages of a sufficiently low dark current, high responsivity, flat spectral response and sufficient bandwidth. We will discuss the performance of our photodetectors in relation to the long-wavelength SS-OCT application. The results are however also relevant to other applications. The devices have an identical structure to the QD optical amplifiers in this wavelength region, and they have been fabricated using the same technology as the QD tunable laser demonstrated earlier and can therefore be easily integrated with it. This makes the QD photodetectors particularly promising for monolithically integrated OCT systems.

In Section 2, the structure and the layout of the devices are presented. In Section 3, measurement methods and results on the dark current, device-length-related and spectrally resolved responsivities, the absorption spectra of the dots and the signal bandwidth of the QD waveguide photodetectors are presented. To interpret and analyze the measurements a theoretical model based on rate equations and an equivalent electrical model of the devices are presented in Sections 4 and 5 respectively. Comparisons between the measurement and theory are also discussed. From this work conclusions which are presented in Section 6 can be drawn on the usability of the InAs/InP(100) QD material for the purpose of photodetection. Both advantages and disadvantages over other material systems are discussed.
2. Device structure and layout

The QD waveguide photodetectors are realized by applying a reverse-bias voltage on a shallowly etched ridge waveguide QD semiconductor optical amplifier (QD-SOA). The QD-SOA structure (shown in Fig. 1(a)) is fabricated using a technology that is fully compatible with the active-passive optical integration scheme of the Inter-University Research School on Communication Technologies Basic Research and Applications (COBRA) at our university [23]. The QD active material is grown on an n-doped InP(100) substrate by metal-organic vapor-phase epitaxy (MOVPE) [24]. Five InAs QD layers are stacked with each layer (3 monolayers (MLs)) grown on top of an ultrathin GaAs interlayer (1 ML). The GaAs interlayers are used to control the size of the QDs. Between each QD layer, 40 nm InGaAsP separation layer is used. This stack of active materials is then placed in the center of the InGaAsP (Q1.25) waveguiding layer with a total thickness of 500 nm. During the MOVPE growth, the average size of the InAs QDs is tuned to have the emission (absorption) spectrum around 1.7 µm [25]. The waveguiding layer is sandwiched by a bottom cladding of a 500 nm n-type InP buffer and a top cladding of 1.5 µm p-type InP layer with a compositionally graded 300 nm p-type InGaAs contact layer. The single-mode shallowly etched waveguide with a width of 2 µm is formed by etching 100 nm into the InGaAsP waveguiding layer using a reactive ion etching (RIE) process. The RIE process is also used to etch isolation sections on the ridge waveguide in order to create sections of varying length and to provide electrical isolation between adjacent sections. The isolation sections are formed by etching away the top cladding layer until 200 nm above the waveguiding layer (see Fig. 1(a)). The structure is then planarized using polyimide before creating the top and backside metal contacts. The structure is cleaved perpendicularly to the waveguide and no coating is applied. The whole layer stack of the QD photodetector is the same as the layer stack of a QD-SOA [23], and is compatible with a butt-joint active-passive integration process for further integration [26]. It opens a possible way to the monolithic integration of the swept laser, the photodetector and the interferometer structure in a single chip.

A photograph of the fabricated chip is shown in Fig. 1(b). A single chip contains an array of 26 QD-SOAs, each of which consists of two sections. The strips of metallization that lie on top of the waveguides are clearly visible. The shorter sections are reversely biased as the QD waveguide photodetectors. The longer sections are used to absorb the residual optical power passing through the photodetectors and prevent reflections from the back facets. The ratio of the lengths of the shorter and longer sections is varied such that a series of devices with different lengths are realized on a single chip. In this paper, we will present the measurement results from two chips with 52 devices in total. One chip has a total length of 4 mm and device lengths range from 200 µm to 1160 µm, the other has a total length of 6 mm and device lengths range from 300 µm to 1740 µm. Note that the metallization pattern is optimized for optical amplifier operation.

![Fig. 1. (a) The cross-section structure of the QD-SOA section and isolation section. (b) The layout of a chip of QD waveguide photodetectors.](image-url)
3. Characterization

3.1 Measurement methods

The dark current, the length-dependent responsivity, the absorption spectra, the spectral response and the optical response to the modulated signal have been measured for the QD waveguide photodetectors. A diagram of the measurement set-up used is shown in Fig. 2. The measurement of the dark current, photocurrent and responsivity of the photodetectors are done with a constant optical input. The measurement of the response to the modulated optical input is done with a sine wave modulation on the input signal. A polarization-maintaining (PM) lensed fiber is used to input linearly polarized light from a tunable laser into the waveguide photodetectors with a coupling loss of $4 \pm 0.2$ dB. The orientation of this PM lensed fiber can be rotated such that the polarization state of the excitation light launched into the waveguide can be controlled. A 1 GHz high-speed probe is attached to the anode (top contact) of the photodetector. It is then connected to the core of an SMA connector. The case of the SMA connector is connected to the cathode (substrate contact) of the photodetector.

The DC measurements are realized by applying a reverse-bias voltage on the SMA connector (i.e., on the photodetector) from a source meter. The source meter also reads out the current values generated in the detector. The dynamic measurement is done by recording and analyzing the temporal response of the photodetector to the modulated optical input. A commercial photodiode transimpedance amplifier module (Ultrafastsensors, CIT735SP) [27] is used to convert the current into a voltage signal and amplify it such that the output voltage signal can be recorded in an oscilloscope (1 GHz bandwidth; 4 GHz/s sampling rate). The bandwidth of the amplifier module is 210 MHz, which is higher than required for the bandwidth of an SS-OCT system. The reverse bias of the photodetector under dynamic measurement is directly supplied by the amplifier module.

![Diagram of the static and dynamic measurement methods.](image)

3.2 Dark current

The dark current consists of the current generated randomly in the diode in the absence of the photon input plus any leakage current that may run along the sides of the ridges under reverse bias.

The dark currents of the QD waveguide photodetectors are measured for 52 devices. The results for four devices of different lengths and for a range of reverse-bias voltages are shown in Fig. 3. Twenty devices turned out to have an excessively high dark current (in the order of mA at a few volts’ bias) which we attribute to a failing of the surface passivation of those devices. For a fixed device length, the dark current of the properly functioning devices increases exponentially with the reverse-bias voltage. The mechanism behind this phenomenon is not certain. This might be attributed to the increase of the side-wall leakage current or to the Zener effect at higher voltages. Clearly the dark current increases proportionally with the increasing device length, i.e., the surface area of the diode. For
devices shorter than 1000 µm, the dark current can stay below 10 nA when the reverse-bias voltage is lower than 2 V. The dark current increases up to 30 nA when reverse-bias voltage is 3 V. Thus from a practical view, the device length should be shorter than 1000 µm and reverse-bias voltage be lower than 3 V in order to maintain a sufficiently low dark current (< 30 nA). When the voltage is increased further the dark current increases rapidly and the operating point becomes impractical.

![Fig. 3. The dark currents under various reverse-bias voltages for different device lengths.](image)

3.3 Responsivity

As discussed in the introduction, the responsivity is a key characteristic of a photodetector for the OCT application. The relationship between responsivity and various operational parameters (e.g., reverse-bias voltage and device length) is important for choosing the most suitable device. In order to explore the responsivity property, a series of measurements are done for 32 out of total 52 devices with different lengths. A laser with a 1640 nm wavelength and 0 dBm optical power is used as the light source. The photocurrents are recorded for each of the 32 devices for four different reverse-bias voltages and for both polarizations. The responsivities are then calculated by calibrating the photocurrents with the input optical power (with a coupling loss of 4 dB).

![Fig. 4. (a) The responsivities of 32 devices with different lengths at a wavelength of 1640 nm. The measurements were done under four different reverse-bias voltages and for both polarizations. The simulated results (which will be discussed in Section 4) are also shown in the figure. (b) The absorption length (for both polarizations) under different reverse-bias voltages.](image)

Figure 4(a) shows the responsivities of all measured devices in all conditions. It is shown in the figure that as the device length increases, the responsivity also increases since more photons are absorbed in the detector. When the device length increases to a certain value, the increment of the responsivity becomes less and the trend becomes flatter. This indicates that after reaching a certain length, almost all the photons are absorbed. Thus little improvement
will be seen for longer devices. Here we define the absorption length to be the length where the responsivity reaches 95% of its maximum. As can be seen in Fig. 4(b), the absorption length is inversely proportional to the reverse-bias voltage. This indicates that the photon absorption of the diode becomes stronger at higher reverse-bias voltages. This phenomenon will be further explored in Section 3.4. It is also obvious that the absorption length of TM polarization is longer than that of TE polarization. This indicates a relatively lower absorption for TM polarization which will be proven by fitting the simulation to the measured data in Section 4.2.

The response of the photodetectors to a scan of input optical power has also been investigated. The wavelength of the input laser is fixed at 1640 nm with an output power of 0 dBm. The laser output is then directed to a tunable attenuator which provides attenuations from −60 dB to 0 dB. The total loss before entering the lensed fiber (including the insertion loss of the attenuator) is 6.04 dB. A coupling loss of 4 dB between the lensed fiber and waveguide is assumed. As the attenuation of the optical power is scanned from −60 dB to 0 dB, the photodetectors generate corresponding photocurrents. The photocurrents are then linearly fitted. We found that within the attenuation range from −20 dBm to 0 dBm, the relative deviation between measured and fitted data is less than 5% for both short (280 µm) and long (1120 µm) devices and for both TE and TM polarizations. When the attenuation increases further, the relative deviation becomes larger because the influence of the dark current cannot be neglected. Saturation is not observed for both short (280 µm) and long (1120 µm) devices.

3.4 Absorption spectra

As is observed in the previous section that the photon absorption becomes stronger at higher reverse-bias voltages, the absorption spectra of the photodetectors have been measured in order to investigate the absorption behavior of the QDs. The measurement is done by reverse biasing the short SOA section (the photodetector) and injecting a current into the long section by forward biasing (see Fig. 1(b)). The injected current density is set to be 3000 A/cm² such that the long SOA section provides an amplified spontaneous emission (ASE) output the power of which is sufficient such that the residual optical power passed through the photodetector is recognizable. The ASE spectrum $P_{ASE}(\lambda)$ from the output facet of the long section is collected by the lensed fiber and recorded by an optical spectrum analyzer (OSA) with a resolution of 0.1 nm. Thereafter the residual optical power $P_r(\lambda)$ which passes through the photodetector is collected from the output facet of the short section for a number of reverse-bias voltages. Figure 5(a) shows the measured spectra for $P_{ASE}(\lambda)$ and $P_r(\lambda)$ for a device length of 600 µm.

The relation between $P_{ASE}(\lambda)$ and $P_r(\lambda)$ can be expressed as follows,

$$P_0(\lambda) = \eta P_{ASE}(\lambda),$$  \hspace{1cm} (1)

$$P_r(\lambda) = \left[ P_{ASE}(\lambda) + P_{ASE}(\lambda) e^{\alpha_{SOA} L_{SOA}} R_f \right] e^{-\alpha_{PD} L_{PD}} \eta,$$  \hspace{1cm} (2)

$$\Rightarrow P_r(\lambda) = e^{-\alpha_{PD} L_{PD}} \left( e^{\alpha_{SOA} R_f} + 1 \right) P_0(\lambda).$$  \hspace{1cm} (3)

where $\alpha(\lambda)$ is the absorption coefficient, $L_{PD}$ the length of the photodetector, $L_{SOA}$ the length of the long SOA section, $P_{ASE}(\lambda)$ the ASE spectrum generated in the long SOA section and $\eta$ the coupling efficiency between the lensed fiber and the waveguide. The facet reflection $R_f$ is taken into account in this calculation since part of the light at the output facet of the long SOA will be reflected back into the SOA. The reflected light will be amplified by the small signal gain of the SOA and will contribute to the input power of the photodetector. Since we have only two sections available in each device we have to make assumptions in the analysis. We assume that the fiber coupling losses of the short and long sections are identical. It should also
be noticed that the measured absorption spectra also include the pure propagation loss of the optical mode in the short detector section. When a method with four SOA sections in the device is used [28] a higher accuracy can be achieved.

![Graph](image)

Fig. 5. (a) The ASE spectrum collected from the output facet of the long SOA section and the residual power collected from the output facet of the short section. (b) The absorption spectra for different reverse-bias voltages.

By applying Eq. (3) to the measured data shown in Fig. 5(a), the absorption spectra for different reverse-bias voltages can be derived (see Fig. 5(b)). It can be found in the figure that the absorption increases with increasing reverse-bias voltage. It is a result of the increased carrier extraction rate in the diode. As the reverse-bias voltage increases, the carriers flow faster out of the QDs which can then absorb another photon. The probability of the QDs being occupied with a carrier pair decreases which results in an increase of the absorption.

### 3.5 Spectral response

The QD waveguide photodetectors have a flat response over a whole 300 nm wavelength range as shown in Fig. 6(b). This well satisfies the requirement for the OCT application. The responsivities of the QD waveguide photodetectors have been measured as a function of wavelength. This is done by scanning the wavelength of the optical input. A device with a length of 960 \( \mu m \) is used. The choice of this length is that this device has a good dark current performance and the length is long enough to absorb most (95%) of the light (see Fig. 4(b)). The photocurrents are recorded for every 5 nm wavelength step and are calibrated with the original optical power of each wavelength. The light sources used for the measurement are a commercial tunable laser which covers a wavelength range from 1.44 \( \mu m \) to 1.64 \( \mu m \), and our QD tunable laser proposed earlier [8] which covers a wavelength range from 1.685 \( \mu m \) to 1.745 \( \mu m \). The measurements are done for four reverse-bias voltages at which the dark-currents are sufficiently low and for both TE and TM polarizations. It should also be mentioned that there is an increasing uncertainty in the data in the wavelength range between 1.685 \( \mu m \) to 1.745 \( \mu m \) since the power meter used in the measurement is not calibrated for wavelengths longer than 1.65 \( \mu m \). The spectral dependency of coupling loss between the fiber and the waveguide facet is also investigated. It is done by calculating the overlap integral between the fundamental mode of the waveguide and the Gaussian mode profile of the lensed fiber as a function of wavelength. The wavelength-dependent waveguide modes are calculated by a finite-difference method (FDM) mode solver. The wavelength-dependent modes and focal lengths of the lensed fiber can be found in [29]. The calculation shows very little wavelength dependency of the coupling loss (see Fig. 6(a)). As in the 1.4 to 1.8 \( \mu m \) wavelength range, the coupling loss is almost wavelength insensitive. The difference between minimum and maximum loss is less than 0.5 dB. The polarization dependency is also very low (< 0.2 dB). Thus the coupling loss has little influence on the spectral responses.
It is clear in Fig. 6(b) that the responsivity of the photodetector increases dramatically with the reverse-bias voltage. When the reverse-bias voltage increases from 0 V to 1 V, the responsivity shows the largest increment. If the reverse-bias voltage increases further, the increase of responsivity is less but still significant. This phenomenon can also be observed in Fig. 4(a). It can be explained as the increase of the carrier extraction rate from the QDs as will be shown and discussed in detail using a QD rate equation model in Section 4. The increase of reverse-bias voltage will enhance the electric field in the depletion region of the diode. As a result, the carrier extraction rate from the QDs increases. It is also obvious from Fig. 6(b) that over the whole wavelength range, the slope of the spectral response curves stays almost the same when the reverse-bias voltage varies. It indicates that when the reverse-bias voltage changes the shape of the absorption spectra of the photodetector does not change (see Fig. 5(b)). It is also clear that the device shows a polarization dependency. This is mainly due to the physical nature of the strained QDs [25,30]. The absorption coefficient at TM polarization will be less than that of TE polarization, thus causing the difference in responsivities.

As a result, when the reverse-bias voltage is 3V, the photodetector provides a very flat response to a wide wavelength range (300 nm) with an average responsivity as high as 0.7 A/W. The high responsivity and flat spectral response show good perspective in the application of SS-OCT systems.

3.6 Bandwidth

To determine the signal bandwidth of the photodetector, sine wave amplitude modulated laser light at a wavelength of 1.55 µm and a power of 3 dBm was launched into the detector with a varying modulation frequency. The modulation depth which is defined as \( \frac{V_{\text{max}} - V_{\text{min}}}{V_{\text{max}} + V_{\text{min}}} \times 100\% \), where \( V_{\text{max}} \) and \( V_{\text{min}} \) represent the average upper and lower envelopes of the signal, is 20% in our measurement.

Figure 7 shows the frequency response of a 280 µm-long photodetector under different reverse-bias voltages. It is clear that the 3 dB bandwidth increases as the reverse-bias voltage increases. This is possibly due to the increase of the depletion region thus decrease of the junction capacitance. As the voltage increases up to 3 V, the 3 dB bandwidth can reach 75 MHz.
Fig. 7. The frequency response of the 280 µm-long photodetector for different reverse-bias voltages when the modulation ranges from 10 to 100 MHz. The data are normalized at 10 MHz.

Fig. 8. The frequency response of the photodetector for different device lengths when the modulation ranges from 10 to 100 MHz at a reverse bias voltage of 2 V. The data are normalized at 10 MHz.

The 3 dB bandwidth is also related to the length of the device. The longer the device, the larger the junction and metal contact capacitances. Thus a shorter device will provide a higher bandwidth (shown in Fig. 8). When the device is as long as 1 mm at 2 V, the 3 dB bandwidth is only 30 MHz. While the device length shrinks to 200 µm, the bandwidth increases significantly to 83 MHz. It should be noticed that, since the lower limit of the modulation frequency in our setup is limited to 10 MHz we had to align the curves at 10 MHz. Therefore the actual bandwidth will be slightly lower than the measured one.

The measured bandwidth is relatively low compared to other waveguide photodetectors [31,32]. The main reason is the large capacitance of the structure. This capacitance is relatively large due to the fact that an n-doped substrate is used in combination with the large 220 µm wide metal contacts as well as the relatively long devices that are needed due to the low absorption of the material. However the measured bandwidth is already close to being sufficient for the OCT application. In Section 5, the main sources which limit the bandwidth will be analyzed by applying an equivalent circuit model on the photodetectors.

4. Rate equation model

In this section, a modified rate equation model analyzing the absorption behavior of the QDs will be presented and analyzed. The rate equations together with the modifications and parameters will be presented first. The responsivities of various devices will be calculated and compared to the measurement results which have been shown in Section 3.3. The spectral response as well as the absorption behavior of the QDs is also simulated and discussed.
4.1 Modified model and parameters

Various rate equation models have been proposed for understanding the gain properties of the QD-SOAs and lasers [23,33,34]. Obviously they are used for the gain analysis with a current injection. Here we present a rate equation model based on a QD-SOA model [23,34] that has been modified for the simulation of photodetection with current extraction.

In Ref [23], a rate equation model was applied to the analysis of the gain in QD-SOA in the 1.6 to 1.8 µm wavelength range. A good match was achieved between the model and the measured small signal gain spectra. It also explained the shape of the gain as a function of the injected current density. Since we used the same QD active material and layer stack for the photodetector, the QD rate equation model and several of the parameters used in [23] were modified to simulate the behavior of the photo-absorption of the QDs. The whole schematic of the structure of the energy band diagram is depicted in Fig. 9 where all the carrier dynamics are also indicated.

![Fig. 9. The schematic of the energy band diagram of the QD active region. The carrier capture and escape rates from the states are indicated.](image)

The model contains a separate confinement structure (SCH) layer where the carriers are extracted out of the QDs and a wetting layer (WL) as a carrier reservoir. The excited state (ES) and ground state (GS) are both allocated into $N$ sub-groups to express the inhomogeneous dot size distribution with each group representing a certain average dot size (energy level). The Gaussian inhomogeneous distribution of dot size is the same as in [23]. The photo-generated carriers in the GS are transferred to ES with an escape rate of $1/\tau_{eGS}$. Then together with the carriers generated in ES, they escape from ES to WL with a rate of $1/\tau_{eES}$. The escape process from WL to SCH ($1/\tau_{eS}$) is assumed to be strongly dependent on the reverse-bias voltage. Finally the carriers are extracted by a very fast process ($1/\tau_{esc}$) due to the high electric field. The carriers can also flow back from SCH to WL, from WL to ES and from ES to GS with capture rates of $1/\tau_s$, $1/\tau_c$ and $1/\tau_d$ respectively. The carriers also experience radiative or non-radiative processes in SCH, WL and two energy states in QDs with a rate of $1/\tau_{sr}$, $1/\tau_{qr}$ and $1/\tau_{dr}$ respectively.

The resulting rate equations are as follows:

$$
\frac{dN_q}{dt} = \frac{N_q}{\tau_{qe}} - \frac{N_q}{\tau_s} - \frac{N_q}{\tau_{sr}} - \frac{N_q}{\tau_{esc}},
$$

$$
\frac{dN_{qs}}{dt} = \frac{N_q}{\tau_s} + \sum_n \frac{N_{Esn}}{\tau_{qEsn}} - \frac{N_q}{\tau_{qr}} - \frac{N_q}{\tau_{qe}} - \frac{N_q}{\tau_{e0}} \sum_n (1 - P_{Esn}) G_n,
$$

where $N_q$ is the number of carriers, $\tau_{qe}$, $\tau_s$, $\tau_{sr}$, $\tau_{esc}$, $\tau_{qEsn}$, $\tau_{qr}$, $\tau_{qe}$, $\tau_{e0}$, and $G_n$ are the capture and escape rates of the carriers, and $P_{Esn}$ is the probability of radiative recombination.
The rate equation model consists of one equation representing the SCH (Eq. (4)), one representing the WL (Eq. (5)), \(N\) equations for ES (Eq. (6)), and \(N\) equations for GS (Eq. (7)). The rate equations are then coupled with one equation for the photons (Eq. (8)) where spontaneous emission (\(\beta N_{\text{spon}}/\tau_r\)) and pure photon loss (\(S/\tau_p\)) are also included.

The major modification from [23] is the change from current injection to current extraction. We set the current injection in the model to zero, and add an additional carrier escape rate \(1/\tau_{\text{esc}}\) from the SCH layer out of the QDs. This parameter presents the fast extraction of the photo-generated carriers due to the high electric field and it is assumed to be much faster than other capture and escape rates in the model. Another modification is that the multiple photon groups used for representing different wavelength components in the gain spectra is reduced to only one photon group which represents a single wavelength as in the measurements.

In the model, the carrier escape times of ES and GS are related with the carrier capture times \(\tau_{c0}\) and \(\tau_{e0}\) in the following way [34]:

\[
\tau_{eESn} = \tau_{e0} \frac{\mu_{ES} N_D V_A}{\rho_{\text{WL}0} V_{\text{WL}}} e^{\frac{E_{ES} - E_{E}\text{ff}}{k_B T}}, \quad n = 0, 1, \ldots, N - 1, \tag{9}
\]

\[
\tau_{eGSn} = \tau_{e0} \frac{\mu_{GS}}{\mu_{ES}} e^{\frac{E_{GS} - E_{E}\text{ff}}{k_B T}}, \quad n = 0, 1, \ldots, N - 1. \tag{10}
\]

where \(\rho_{\text{WL}0}\) is the effective density of states in the WL, \(V_A\) and \(V_{\text{WL}}\) the volume of the QD active region and the WL, \(\mu_{ES}\) and \(\mu_{GS}\) the degeneracy of ES and GS, and \(N_D\) the dot density.

The extraction of the photocurrent is represented in Eq. (4) by the escape rate from SCH out of the QDs (\(1/\tau_{\text{esc}}\)). The relation between the photocurrent \(I_p\) and \(\tau_{\text{esc}}\) can be written as:

\[
I_p = e \frac{N_D}{\tau_{\text{esc}}}. \tag{11}
\]

During the calculation, the absorption coefficients of ES and GS of the QDs are calculated with the following equations:

\[
\alpha_{ESn} = \mu_{ES} C_g \frac{N_u N_D}{H_{\text{act}}} \frac{p^{\mu}_{E\text{S}\text{S}}}{E_{ES}} (2P_{ESn} - 1) G_u B_{cv} (E_{\text{photon}} - E_{ESn}), \tag{12}
\]

\[
\alpha_{GSn} = \mu_{GS} C_g \frac{N_u N_D}{H_{\text{act}}} \frac{p^{\mu}_{G\text{S}\text{S}}}{E_{GS}} (2P_{GSn} - 1) G_u B_{cv} (E_{\text{photon}} - E_{GSn}). \tag{13}
\]

where \(C_g\) is a constant, \(N_u\) the number of QD layers, \(H_{\text{act}}\) the total active layer thickness, \(|p^{\mu}_{E\text{S}}|, G_u\) the transition matrix elements of ES and GS recombinations [33] and \(B_{cv}\) the Lorentzian
homogeneous broadening function [33]. The total absorption of the photons is then calculated by:

\[ \alpha = \Gamma \sum_n (\alpha_{ESn} + \alpha_{GSn}) \]  

(14)

where \( \Gamma \) is the confinement factor of the QD active layer. All the values of the parameters fixed in the rate equation model are summarized in Table 1. During the simulation, \( \tau_{qe} \) is used to represent the different carrier extraction rate due to different reverse-bias voltages. This is the only parameter that is adjusted to match the calculated responsivities to the measured ones. For TM polarization, the transition matrix element \( |P_{\sigma ES, GS}|^2 \) is also adjusted to fit the simulations to the measurements. This is because only TE polarization was considered and described in the simulation of QD-SOAs in [23].

Table 1. Parameters used in the rate equation model

| Parameters                                      | Values                              | References |
|-------------------------------------------------|-------------------------------------|------------|
| FWHM of inhomogeneous broadening                | \( \Gamma_0 = 41 \text{ meV} \)    | [37]       |
| Effective density of states of WL               | \( p_{WLeff} = 2.4 \times 10^{11} \text{ cm}^{-2} \) \( (T = 288 \text{ K}) \) |            |
| FWHM of homogeneous broadening                  | \( 2\hbar \Gamma_c = 40 \text{ meV} \) | [23]       |
| Degeneracy of ES                                | \( \mu_{ES} = 4 \)                 |            |
| Degeneracy of GS                                | \( \mu_{GS} = 2 \)                 |            |
| Relaxation time from SCH to WL                  | \( 7 \text{ ns} < \tau_r < 20 \text{ ns} \) | [23]       |
| Capture time from WL to ES                      | \( \tau_{0,c} = 1 \text{ ps} \)     | [37]       |
| Capture time from ES to GS                      | \( \tau_{0,d} = 1 \text{ ps} \)     | [37]       |
| Escape time from SCH to outside                 | \( \tau_{esc} = 0.1 \text{ ps} \)   |            |
| Carrier recombination time in SCH               | \( \tau_x = 4.5 \text{ ns} \)       | [38]       |
| Carrier recombination time in WL                | \( 2 \text{ ps} < \tau_x < 100 \text{ ps} \) | [23]       |
| Carrier recombination time in ES and GS         | \( \tau_x = 1 \text{ ns} \)         | [37]       |
| QD density                                      | \( N_D = 3.1 \times 10^{10} \text{ cm}^{-2} \) | [24]       |
| Number of QD layers                             | \( N_w = 5 \)                       |            |
| Total active layer thickness                    | \( H_{act} = 200 \text{ nm} \)      |            |
| Refractive index                                | \( n_r = 3.261 \)                   |            |
| Optical confinement factor                     | \( \Gamma_{TE} = 0.34; \Gamma_{TM} = 0.33 \) \( @1.7 \mu m \) \( \text{(wavelength dependent)} \) |            |
| Transition matrix elements (for TE)            | \( |P_{\sigma ES, GS}|^2 = 2.70 \text{ m}\mu E_{Ex,Gy} \text{ kg eV} \) | [23]       |
| Internal modal loss                             | \( \alpha_i = 10 \text{ cm}^{-1} \) \( @1.7 \mu m \) \( \text{(wavelength dependent)} \) |            |
| Temperature                                     | \( T = 288 \text{ K} \)             |            |
| Number of QD sub-groups                         | \( N = 61 \)                        |            |

The rate equations are solved in the time domain. They are integrated in time till a steady state has been reached [23]. During the simulation, an instant carrier extraction from SCH out of the QDs is assumed \( (\tau_{exc} = 0.1 \text{ ps}) \) due to the high electric field. All the carriers escaping from WL to SCH will be instantly extracted by this fast process. As long as \( \tau_{exc} \) is shorter than 10 ps, it does not significantly influence the simulation results any further. The escape rate from WL to SCH is determined to be dependent on the reverse-bias voltage to represent the voltage-dependency of the carrier extraction rate mentioned in Section 3.3. The optical confinement factors of the active region for TE and TM polarizations are calculated over the whole wavelength range \( (1.4 \mu m \text{ to } 1.8 \mu m) \) using an FDM mode solver (see Fig. 10(a)). The wavelength dependency of the internal modal loss \( \alpha_i \) is also considered as shown in Fig. 10(a). One can clearly see the loss for longer wavelengths is much higher than that for shorter wavelengths due to the higher overlap of the optical mode and the highly doped p-type cladding layers.
Fig. 10. (a) The wavelength dependency of the optical confinement factors (for both TE and TM polarizations) and the internal modal loss. (b) The values of $\tau_{qe}$ at different reverse-bias voltages.

4.2 Comparison with experimental results

The simulation is first performed at an optical input with fixed wavelength and fixed optical power for TE polarization. The device length is scanned from 200 $\mu$m to 2000 $\mu$m. The carrier escape rate from WL to SCH ($1/\tau_{qe}$) is the only parameter that is adjusted to match the simulation with the measured data for one particular value of the reverse-bias voltage. The relation between $1/\tau_{qe}$ and the reverse-bias voltage is shown in Fig. 10(b). The increase in the rate represents the increase of the reverse-bias voltage.

The simulated results for all the devices are shown in Fig. 4(a) in dashed curves. As can be seen in the figure, the simulation results match very well with the measured data. For TM polarization, we use the same set of $\tau_{qe}$ since the carrier dynamics is not expected to change with the polarization state of the incident light. The optical confinement factors for TM polarization need to be used. The transition matrix elements are also adjusted for TM polarization to represent the polarization dependency of the QDs. After the simulated result being fitted to the measured data, the transition matrix elements decrease from $2.70 m_0^2 E_{EG,GS}$ for TE polarization (as shown in Table 1) to $2.30 m_0^2 E_{EG,GS}$. The lower transition matrix elements for TM polarization indicate lower absorption coefficients ($\alpha_{ES, TM}$ and $\alpha_{GS, TM}$) according to Eq. (12) and Eq. (13).

Simulations for the spectral behavior of the photodetectors are also performed. The spectral simulations for a 960 $\mu$m-long device under TE polarization are performed (as shown in Fig. 11(a)). The situation is similar for TM polarization. It can be seen in the figure that for wavelengths longer than 1.6 $\mu$m, the simulation matches well with the measured spectrum. But for the shorter wavelengths below 1.6 $\mu$m, there is a clear deviation between simulation and measurement. The reason of this deviation is that the absorption coefficient of the QDs in the shorter wavelength region is underestimated. As can be seen in Fig. 11(b), the photon absorption $\alpha$ (Eq. (14)) of the device is calculated for TE polarization. It shows that the calculated photon absorption in the shorter wavelength region is lower than that in the longer wavelength region. On the other hand, the measured photon absorption in the shorter wavelength region is higher than that in the longer wavelength region (see Fig. 5(b)). It is possible that the photon absorption is underestimated due to the exclusion of the contributions from higher energy states in the QDs. Such states would not show up in the ASE spectra in forward bias, but can play a role in absorption. Also absorption in the WL was not included in our model. The energy level of the WL corresponds to a wavelength of 1.47 $\mu$m [23] and is indicated as a blue dashed line in Fig. 11(a). This wavelength is in the wavelength region where a clear deviation occurs. Thus the exclusion of absorption from WL is the most likely reason for the deviation. According to our simulation, the photodetectors still provide high responsivities for wavelengths beyond 1.8 $\mu$m (e.g., 0.6 A/W at 2 $\mu$m, 3 V).
5. Equivalent circuit model

In this section, an equivalent electrical circuit model is applied on the QD waveguide photodetectors to analyze the factors that limit the bandwidth of the devices. The simulated bandwidth is matched to the experimental results in order to determine the capacitances in the circuit.

5.1 Equivalent circuit modeling

The QD waveguide photodetectors can be modeled by an equivalent circuit method [35] as shown in Fig. 12. $I_{d}(\omega)$ is the photon-generated current paralleled by the junction capacitance $C_{pd}$ and junction resistance $R_d$. A time-independent reverse-bias voltage $V_r$ is applied on the photodetector. The device is in series with a series resistance $R_s$ and then in parallel with the probe pad capacitance $C_p$. The photodetector is connected with the commercial photodiode amplifier module [27], which has an input capacitance ($C_i = 7$ pF) and an input load ($R_L = 50 \Omega$). The series resistance $R_s$ is estimated to be about 7.6 $\Omega$ using the method presented in [31]. The junction resistance $R_d$ can be neglected when the dark current is very low ($<< \mu A$). The $C_{pd}$ and $C_p$ are adjusted during the simulation to match the simulated bandwidth to that of the measured one.

The frequency response of this circuit is the product of the frequency response of the $RC$ circuit and the frequency response of the amplifier module. According to [31], the frequency response of the $RC$ circuit can be written as

$$H_{i}(\omega) = \frac{1}{1 + j\omega(C_{pd}(R_s + R_d) + R_s(C_s + C_p))} - j\omega R_s R_d C_{pd}(C_s + C_p).$$

Fig. 11. (a) The spectral simulations of a 960 $\mu$m-long device for TE polarization. The measured spectra are also shown for comparison. (b) The total photon absorption of the QDs calculated by the rate equation model (also for TE polarization).
The frequency response of the amplifier module $H_2(\omega)$ can be directly measured by a network analyzer. Thus the overall frequency response is the product of $H_1(\omega)$ and $H_2(\omega)$.

The total bandwidth of the photodetector can be written as $1/f_{\text{total}}^2 = 1/f_{\text{circuit}}^2 + 1/f_{tr}^2$, where $f_{\text{circuit}}$ is the 3 dB bandwidth of the equivalent circuit and $f_{tr}$ the transit time bandwidth which is determined by the carrier drift time in the photodetector. Since $f_{tr}$ is very large (> 40 GHz [31]) compared to $f_{\text{circuit}}$, it can be neglected for simplicity.

5.2 Comparison with experimental results

The junction capacitance $C_{pd}$ and probe pad capacitance $C_p$ are first determined for a device with a fixed length and a range of reverse-bias voltages. The $C_{pd}$ should be inversely proportional to the applied voltage since as the voltage increases the junction capacitance will decrease due to an expansion of the depletion region. The $C_p$ on the other hand will not change as the voltage. Thus by matching the simulated 3 dB bandwidth with the measured one, the value of $C_p$ and voltage dependency of $C_{pd}$ can be determined. The frequency responses of the amplifier module, the equivalent circuit and the overall model of a 280 µm-long device under 2 V reverse bias are shown in Fig. 13(a). The determined values of $C_{pd}$ and $C_p$ under different reverse-bias voltages are shown in Fig. 13(b). As $C_p$ does not change as voltage, it keeps a relative high value (as high as 46 pF). This is mainly due to the large area of the metal contact used in our devices (220 µm wide and same length as the device). It can also be seen that there is a significant improvement on $C_{pd}$ as the reverse-bias voltage increases. The error bars of the $C_{pd}$ in Fig. 13(b) indicate the variability of $C_{pd}$ when the ± 5% relative deviation of the bandwidth values used in the calculation is considered.

![Fig. 13. (a) The frequency responses of the amplifier module, the equivalent circuit and the overall model of a 280 µm-long device under 2 V reverse bias. (b) The determined values of $C_{pd}$ and $C_p$ under different reverse-bias voltages.](image1)

![Fig. 14. The measured and simulated 3 dB bandwidth vs. the device length.](image2)
After determining the capacitances for a device with a certain length, the capacitances for devices with other lengths can be easily estimated because both $C_{pd}$ and $C_p$ are linearly proportional to the device length. Then the relation between the 3 dB bandwidth and the device length can be simulated based on the results obtained at 280 µm length and compared with the measured results. As can be seen in Fig. 14, the simulated bandwidths match well to the measured ones. The figure shows that the length of the device strongly affects the 3 dB bandwidth. According to our model, the 3 dB bandwidth of the device is mainly limited by $C_p$. Thus the bandwidth can be easily improved by optimizing the metallization of the photodetectors.

6. Conclusion

In this paper we have presented the QD waveguide photodetectors and have shown them to meet requirements for application in OCT in the 1.6 to 1.8 µm wavelength range. By choosing a relatively short device (280 µm) and applying a reverse-bias voltage (3 V) these requirements can be met. A low dark current (~15 nA) and flat spectral response (> 0.5 A/W over 300 nm wavelength span) can be achieved. The dark current is of the same magnitude as the InGaAs detectors and much smaller than that of the SWIR InGaAs detectors. The responsivity is also much higher than photodetectors of the InGaAs type. And the flatness of the spectral response is more advantageous compared to all other candidates (e.g., InGaAs, SWIR InGaAs and Ge types). The rate equation model was applied to understand the carrier dynamics in the QD material. The model explains well the absorption behavior of the QDs in the 1.6 to 1.8 µm wavelength range and shows a good match to the experimental results for the length-dependent responsivities. High responsivities for wavelengths beyond 1.8 µm can still be expected according to this model. An equivalent circuit model was also applied. By matching the simulated bandwidths with the measured ones, the capacitances which dominate the bandwidth are estimated and analyzed. The device provides a 3 dB bandwidth of about 70 MHz which is sufficient for OCT application. According to the simulation, bandwidths well over 200 MHz should be achievable with optimized metallization. The QD waveguide photodetectors have also shown potential in other applications such as near-infrared spectroscopy and gas sensing.

There are also several improvements which can be made. For instance, the photon absorption of the active material can be improved by using a new QD material with higher dot density [36]. This will significantly shorten the length of the device and metal contact and will thus help to improve the bandwidth. The layer stack of the photodetector can also be adjusted for less overlap between the optical mode and the highly-doped InP contact layer. The improvement on the propagation loss will increase the maximum achievable responsivity. However this will reduce the performance of the layerstack when being used as an optical amplifier. A spot-size converter might also be included to improve the coupling efficiency between the waveguide and the optical fiber.

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