Miniaturizing optical coherence tomography

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Abstract
Optical coherence tomography (OCT) has revolutionized ophthalmic diagnosis as a non-invasive, cross-sectional imaging technique in the last 30 years and hence is one of the fastest adopted advanced imaging technologies in the history of medicine. A miniaturization of OCT devices would not only reduce size but ideally also reduce costs and therefore create potential new markets. OCT systems based on photonic integrated circuits (PIC) could enable a significant miniaturization of complex systems with high degree of integration as well as low costs of goods. These therefore have a potential to enable portable, cost-effective, high performing, real handheld OCT devices. This review identifies three main categories towards miniaturized OCT devices: Handheld imaging probes interfaced to a (mobile) base station, compact home/self- OCT and PIC-based OCT. Imaging performance parameters and technical readiness levels of the identified miniaturized OCT systems for (non-) ophthalmic applications are presented. Special attention is paid to PIC-based OCT applications and their progress.

Picture: First in vivo human retinal tomogram using a PIC-based subcomponent (arrayed waveguide grating, AWG) of a spectral domain OCT system. Adapted with permission from E. A. Rank et al., *Light Sci Appl.* 2021, 10, 1, CC By 4.0. Copyright © 2021, The Author(s).

Keywords
handheld OCT, home OCT, miniaturization, optical coherence tomography, photonic integrated circuits

Abbreviations: AMD, age-related macular degeneration; AWG, arrayed waveguide grating; CMOS, complementary metal-oxide-semiconductor; FD-OCT, Fourier domain optical coherence tomography; FPGA, field programmable gate arrays; HH, handheld; L-OCT, linear optical coherence tomography; OA-FF-TD-OCT, off-axis full field optical coherence tomography; OCT, optical coherence tomography; PIC, photonic integrated circuit; SD-OCT, spectral domain optical coherence tomography; SS-OCT, swept source optical coherence tomography; TD-OCT, time domain optical coherence tomography; TRL, technical readiness level; WGT, waveguide technology.

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1 | INTRODUCTION

Since its inception 30 years ago, optical coherence tomography (OCT) has gone through an incredible development and has become a standard of care in ophthalmology, impacting millions of people every year [1, 2]. More recently, OCT is expanding its application to a variety of other fields such as dermatology [3], cardiovascular medicine [4], gastroenterology [5], neurology [6] or dentistry [7]. To date, more than 74 000 OCT papers have been published, 6800 in 2020 alone. This corresponds to nearly one publication per hour in this field of research [8].

Current commercial OCT systems for medical care cost up to $180 000, have a footprint of ~1 m² and weigh around 30 kg. These parameters, that is, costs, size and weight, are the three major reasons for OCT being only available in clinics and large practices [9]. Potential new applications for OCT could greatly benefit from miniaturization of these devices. Compact and cheaper OCT devices could be afforded by smaller/private ophthalmic practices, increasing early detection of diseases. They might as well open new markets as screening devices in general practices and low-resource settings. In ophthalmology, a compact patient operated device could improve regular therapy and treatment monitoring [10]. Furthermore, the investigation and monitoring of micro-gravity induced (pathological) retinal changes in astronauts could benefit from a compact, lightweight OCT device on space stations [11]. Therefore, depending on the field of application, the need for a miniaturized OCT system might not only describe the reduction in size, but also the additional need for increased mobility/flexibility or a reduction of device costs. Driven by clinical needs researchers and engineers were inspired to package OCT systems in compact mobile carts, and to develop flexible sample arms within handheld probes [12]. Achievements in further reducing the size of the OCT engines as well as attempts to reduce costs of OCT systems using off-shelf components in combination with smart packaging were discussed recently [13]. OCT systems packaged in a mobile cart with flexible handheld probes typically show good imaging performance and are already commercially available [14–17]. Although systems with increased mobility and flexibility that maintain a good imaging performance exist, the size reduction of the whole system is limited. More compact or cheaper systems currently show a tradeoff between reduced form factor and reduced imaging quality (ie, reduced sensitivity, resolution and/or speed).

Photonic integrated circuits (PIC) have the potential to overcome the above-mentioned limitations. They are considered an attractive alternative in data- and telecommunication, where the limitations of electronics like integration density and heat generation could be overcome by using light-based circuits [18]. State-of-the-art fiber- and free space-based optoelectronic components typically provide one single functionality (ie, a laser, an interferometer or a detector) and need to be assembled to a complex system. PICs consist of structures like waveguides, passive and active building blocks (eg, light sources, modulators, couplers, interferometers, gratings or photodiodes), which can be photolithographically printed on a single chip simultaneously, resulting in a combined optoelectronic system [19]. They can be fabricated from a variety of materials; however, silicon-based types have become the predominant material of choice because they are compatible with the well-established silicon-based complementary metal-oxide-semiconductor (CMOS) fabrication processes [20, 21]. Already available simulation models, fabrication processes and tools can be used to implement wafer-scale fabrication processes for PIC- and CMOS-based optoelectronic systems [22]. Dozens of PICs are fabricated in parallel, which reduces the production costs of single units. The fabrication of an optoelectronic system on one monolithic chip, including the optical system, detection as well as electronic (pre-) processing, can therefore be achieved in a single fabrication plant without the need for post fabrication assembly.

The above-described advantages of PICs have several limitations. First, in case of small production volumes, the costs of PIC fabrication are similar to conventional methods. To produce truly cheap systems it would be necessary to divide these costs over millions of units [23]. Recent developments in programmable PICs, that is, reconfigurable PICs, might be a solution for niche markets, such as OCT [24]. These could be produced at scale and a variety of customers and end users, could program these to their specific needs, just like field programmable gate arrays (FPGA) in the electronic processing area. Second, the development of PICs is time intensive. The turnaround time for iterative improvements takes several months. Hence, a great amount of time and money is needed for the development of PIC-based devices until processes are well established. Finally, a connection from PIC to non-PIC components, such as laser to PIC or PIC to imaging optics in the sample arm, is currently still needed for a complete OCT system. These connections are associated with relatively high losses. Especially in in vivo medical applications the coupling losses cannot be compensated by more powerful light sources due to laser safety limitations. A (nearly) lossless connection between PIC and non-PIC will be one of the key parameters for a successful acceptance of PICs.
This work presents and discusses research on miniaturized OCT, focusing on achievements on PIC-based OCT. Three main categories are discussed:

- OCT using handheld probes, including all systems that are packaged on a mobile or portable base station, and a handheld scanning probe to reach the sample of interest.
- Home/self-OCT, summarizing systems that are compact enough for a patient to take home and potentially could be operated by the patient without professional supervision. These might include handheld probes.
- PIC-based OCT, including all reported systems where at least one component was replaced by a PIC.

2 | METHODS

A keyword-based publication search was performed using Boolean search strategy. The defined keywords, as summarized in Figure 1A, were conditioned and searched on

![Figure 1](image)

**Figure 1** Keywords and search strategy. (A) Keywords used for the Boolean-based literature search grouped in different categories: basic OCT terms are conditioned with handheld probes (HH), photonic integrated circuits (PIC) and general terms in the category miniaturization. All keywords were conditioned as depicted in the last line and searched for in title T or abstract A. (B) Flow diagram summarizing the search and screening method. After manual duplicate removal, the publications were screened for eligibility, and three additionally identified articles were included. Out of these 72 included articles, 24 were on PICs.
RESULTS AND DISCUSSION

The keyword-based Boolean search revealed 2712 and 922 articles on Web of Science and PubMed, respectively, adding to a total of 3634 records. Automated filtering functions on these websites excluded non-English articles. After removing duplicates, 1133 articles were screened for eligibility and 69 articles fulfilled the inclusion criteria. These 69 articles were searched on ConnectedPapers.com, which revealed three additional articles fulfilling the inclusion criteria, leading to a total of 72 included publications. Out of these, 24 reported on a PIC-based OCT system, while the remaining 48 articles describe systems with a wired handheld probe \(N = 40\) or home/self OCT \(N = 8\) systems using conventional optical components. Sixteen articles report on an improved version of a system within a previous publication and/or proceeding. In such cases, only one system was included for statistical analysis. Three articles in the PIC-based category report on two different systems within one article, which were included individually in the statistical analysis. Hence, a total of 59 systems were included in the analysis. The complete list of included articles, extracted data and further details on parameter extraction can be found in Table S1.

The technical readiness level (TRL) of the systems was assessed according to the definition in Table 1 using the information provided in the articles.

Figure 2 gives an overview of the relations of the extracted key parameters of all included articles. Fifty percent of the publications were categorized as handheld probes. PIC-based imaging was demonstrated in 36% and home/self-OCT systems were demonstrated in 10%. Swept source (SS-)OCT and spectral domain (SD-)OCT were the most prevalent OCT variants, represented with 42% and 51%, respectively. The time domain (TD-) OCT section includes two articles on multiple reference TD-OCT [27, 28] and one record uses off-axis full-field (OA-FF) TD-OCT [29]. One record uses linear (L-) OCT [30]. In the category central wavelength, 800 and 1300 nm are the two predominant wavelength regions, representing the two main wavelength regions used for ophthalmic and skin imaging, respectively. Thirteen percent of the records used OCT systems centered at 1060 nm, a wavelength region that has shown to achieve comparable axial resolution like 800 nm and at the same time contrasts signal from deeper layers and is less sensitive to ocular haze. Imaging systems at 1550 nm (5%) were reported by PIC-based systems only, indicating that the wavelength region around 1550 nm does not have significant advantages over 1300 nm in OCT but PIC technology is probably most mature in this wavelength region originating from telecommunication applications. Acquisition speed as measured by A-scan rate is in most of the articles below 100 kHz (85%). More than half (54%) of the systems achieved an axial resolution finer than 10 μm. Looking at systems that are designed for ophthalmic application (wavelength regions 800 and 1060 nm), where an axial resolution finer than 10 μm is typically desired, 82% of these achieved such a fine resolution. It is interesting to notice that a total of 36% or 21 systems did not report on system sensitivity, 19 articles of these are in the category of handheld probes. Only one third (34%) reported on a sensitivity above 90 dB, which is typically required for clinical usage. Since sensitivity is strongly dependent on power applied to the sample as well as imaging speed, normalized sensitivity values are desirable. The applied power on the sample ranged between 50 μW and 26 mW, and imaging speed ranged between 0.15 and 800 kHz \((8 \times 100 \text{ kHz})\) across all articles, strongly limiting the comparability of system sensitivity. Most of the systems are categorized in TRL 3 and TRL 4, whereas 80% of all TRL 3 systems are in the PIC section and 68% of all TRL 4 systems are handheld probes.

OCT using handheld probes and home/self-OCT

To access the organ of interest properly, handheld probes have been developed to decouple the sample arm from the stationary or mobile base station (including optics, electronics, computer and a screen) of the OCT system. This flexibility opens up the possibility to image the retina of immobile/bedridden patients or infants, skin areas that are not accessible easily, ear-nose-throat measurements, or even large animals [31] and plants [32] can be imaged. In the last decade, handheld probes have proven their value in imaging the retina [33–46], hair follicles [47] and the tympanic membrane in the ear [30, 48, 49], to detect and monitor skin cancer [50, 51] or skin and mucosal lesions [52–58], and as an imaging tool to assist in surgery [59, 60].
A total of 32 systems reporting on handheld probes are included in this review: this category is the only one in which systems operating at 1060 nm were reported and almost 60% of the articles did not report on a system sensitivity. Size, weight and ergonomic design of handheld probes have been reported to be the three main challenges for clinical acceptance. These aspects can cause motion artifacts introduced by the operator and typically a learning curve in handling the probe is required until reproducible and reliable data can be acquired. Especially in retinal imaging the weight of a handheld probe was reported to be of significant importance for successful imaging and ergonomic considerations were requested by clinical operators [43]. To reduce the weight and size, compact MEMS mirrors [36–39, 41, 57, 59, 61, 62] and light-weight 3D printed lens holders and housing can be used. 3D printing furthermore enables ergonomic design considerations [38, 44, 63]. Handheld probes with various lens adapters appropriate for retinal, inner ear or other tissue, like skin imaging might combine several individual OCT systems for different applications in one [40].

A reduction in size of the entire OCT system has been accomplished by smart packaging, customized optical design and non-traditional OCT techniques, which are summarized as home-/self OCT systems. A total of six systems were included in this category. Low-cost compact commercially available spectrometers for entertainment...
purposes were adapted for OCT application to enable packaging of the whole system (including laptop) in a briefcase [64–67]. Non-traditional OCT techniques, such as OA-FF-OCT [29] and multi-reference OCT [28, 29], which can be built in a very compact way, have been demonstrated for ophthalmic and dermatologic imaging, respectively. The former one was evaluated within a clinical trial [68] and is currently being commercialized [69]. A novel patient interface design for a retinal patient-operated OCT system (“Mimo OCT”) was proposed and validated within a safety and feasibility study by Maloca et al. [70], as shown in Figure 3A. A patent for this system was filed by Mimo AG [72]. A similar approach was taken by Notal Vision “Home OCT” [73, 74] (Figure 3B). A recent clinical trial study demonstrates that age-related macula degeneration (AMD) patients were successfully self-operating the device [74].

Looking at the distribution of parameters in the home/self-OCT category, the most prevalent imaging technique is SD-OCT, all included systems operate in the wavelength region of 800 nm and most of them are operated at an acquisition speed ≤20 kHz.

3.2 Photonic integrated circuits (PIC)-based OCT

PIC-based OCT has the potential to truly miniaturize OCT systems with a footprint of a few cm² and a high integration density. The first attempt of a PIC-based OCT system already demonstrated this by integrating eight parallel Michelson interferometers for in vivo skin imaging using TD-OCT in 2000 [75]. For one decade there have not been any publications about PIC-based OCT, to the best of our knowledge, until PIC-based SS-OCT was presented in 2010 [76]. In 2013 the first in vivo skin imaging using Fourier domain (FD)-OCT was presented [77] and more than two decades after the first attempt, the first in vivo retinal imaging was demonstrated in 2021 [78]. All these milestones in PIC-based OCT only used individual PIC-based components to replace the state-of-the-art fiber or free-space component. There are a few more complete PIC-based OCT systems that partially have been introduced to the commercial market already [79], other promising options are on the horizon.

A total of 18 articles in this review used PIC-based OCT approaches. As mentioned earlier, three articles describe two different systems in one article and therefore were used as individual systems in the statistical analysis. Two articles report on two different arrayed waveguide grating (AWG) designs each, one for a small and large bandwidth [78] and one on two systems with different wavelength regions (AWGs for 800 nm and 1300 nm, respectively) [80]. One article reported on two different PIC designs for SS-OCT, one with an on-PIC and one with an external (standard free-space) reference arm [81]. Therefore, a total of 21 systems were included for statistical analysis. The key parameters extracted from the individual systems are summarized in Table 2 and the relation of the individual parameters are graphically presented in Figure 4.

More than half (52%) of all PIC-based systems were developed for SS-OCT and only 33% achieved a sensitivity ≥90 dB. Most of these systems (62%) operate at a wavelength range of 1300 nm, typically used for dermatologic and inner organ imaging and this category is the only one demonstrating OCT systems centered at 1550 nm. PICs were initially developed for data- and telecommunications, using the same wavelength region and therefore it seems rather straightforward to use already available technologies. For ophthalmic imaging, that is, wavelengths below ~1100 nm are desired, PIC-based OCT was demonstrated at 800 nm only. 52% of the systems show a TRL 3, demonstrating experimental proof of concept.

**Figure 3** Home/self-OCT systems using novel patient interface. (A) “MIMO OCT” device which was tested within a feasibility study. Adapted with permission [70]. CC By 4.0. Copyright © 2018, The Author(s). (B) Notal Vision “Home OCT” for patient operated self-imaging. Reproduced with permission [71]
More than a third (38%) of these systems are categorized in TRL 4 as these were validated in the lab. In most of the articles (72%) only individual components are integrated on a PIC: Either photonic parts, such as interferometer [76, 85–87, 89, 91, 98], AWGs [78, 80, 83, 95, 100], a delay line [96] and parallelization [75, 89] or electronic/detection part [88] have been reported. 19% report on systems that combine on-PIC photonics and electronics or are packaged in a complete compact system [81, 92, 94].

Three main material combinations have been reported in PIC-based OCT: Silicon on insulator (SOI), silicon nitride (Si₃N₄) and silicon oxynitride (SiON) [21, 101–103]. The SOI platform is transparent at wavelengths above ~1100 nm, while Si₃N₄ and SiON are transparent in the wavelength region of 210 nm - 2000 nm [104, 105], making these suitable candidates for ophthalmic OCT systems. Therefore, the two following sections will discuss PIC-based OCT > 1100 nm and for the 800 nm region.

### 3.2.1 | PIC-based OCT for the >100-nm region

The majority of all PIC-based OCT systems (76% or 16 out of 21 systems) operate at a wavelength region above 1100 nm. Most of these reported on interferometer on the PIC, either in Michelson [76, 85, 87], Mach-Zehnder [86, 91] or common path configuration [89].

The first PIC-based Michelson interferometer for SS-OCT in 2010 suffered from losses of the used grating couplers, as depicted in Figure 5A, and reduced the sensitivity by 24 dB [76]. Facet roughness further reduced the sensitivity and a system sensitivity of 25 dB was measured. The dispersion, introduced by waveguide dimensions, was challenging. In an improved version of the system the grating coupler was reported to have insertion losses of 7.5 dB [82, 86]. The dispersion was improved and a system sensitivity of 62 dB was measured. The same group reported on a PIC-based Mach-Zehnder interferometer for SD-OCT using edge coupling (instead...
of grating couplers) with a coupling loss of 4.5 dB fiber to PIC coupling [87]. With an on-PIC reference arm, this system achieved a system sensitivity of 62 dB. A PIC-based Michelson interferometer for SS-OCT with edge couplers was reported with coupling losses between 1.5 and 3.5 dB (fiber to PIC and PIC to fiber, respectively) [85]. A sensitivity of 80 dB and an axial resolution of 12.7 μm were measured. Although not specifying concrete values, a more recent demonstration of a PIC-based Mach-Zehnder interferometer for SS-OCT discusses that the losses of coupling in and out of the PIC have significantly contributed to reduced system sensitivity [91].

The results of an on-chip common path SS-OCT are shown in Figure 5C [89]. The back-reflection from the end facet of the sample arm waveguide was used as reference signal, making the need for dispersion compensation obsolete. An on-chip microball lens was integrated on the PIC to increase coupling efficiency. Although the microball lens has the disadvantage of an additional component that has to be aligned, the signal enhancement was measured to be up to 37 dB. A system sensitivity of 71 dB was measured with this system. In the common-path configuration dual balanced detection is not possible, reducing the sensitivity. Furthermore, the reference arm was too short to implement scanning mirrors and the sample had to be moved on a translational stage.

Two systems report on an on-PIC replacement for a diffraction grating, the AWG [77, 80, 83, 84]. In an AWG broadband light, coming from an input waveguide, diverges in a free propagation region towards an array of waveguides with increasing length, also called phased array [106]. Each waveguide in the phased array guides a portion of the input light and the linearly increasing length of the waveguides creates phase delays. At the output of the phased array the light transverses in a free-space region and wavelengths with the same phase delay interferes at the entries of the output waveguides. The individual output waveguides then forward individual wavelengths towards on-chip photo diodes or to the end-facet of the PIC, each corresponding to one pixel in conventional SD-OCT systems. AWGs are complex building blocks and it is challenging to design and fabricate these with a high output channel count (in OCT 2048 pixels per A-scan are conventional standard) and at the same time low insertion losses. The first AWG for OCT application had 195 output channels and a system sensitivity of 75 dB was achieved [80, 84]. In a further step, an on-PIC 50/50 coupler was integrated with the AWG for in vivo skin imaging as demonstrated in Figure 5B [77]. Although the system only achieved a sensitivity of 74 dB with 500 μW on the sample and 47 kHz imaging speed, it was demonstrated for the first time that in vivo imaging using AWGs is possible and generates tomograms with fine resolution (7.5 μm axially).
The potential of an on-chip reference arm was investigated in one article [96]. This tuneable delay line was designed with integrated platinum microheaters exploring the thermo-optic effect of Si$_3$N$_4$ and was tested in combination with a commercial OCT system, where the imaging depth was extended by the tuning range of the delay line (0.6 mm).

**FIGURE 5**  (A) First reported PIC-based SS-OCT: chip design including grating couplers for laser input and detection, respectively, a coupler with an on-chip reference arm and a sample arm path, which exits the PIC end-facet horizontally. An A-scan acquired with the system is presented. Reproduced with permission [76]. © Proc. SPIE 7554, Optical Coherence Tomography and Coherence Domain Optical Methods in Biomedicine XIV (75541B) (B) Setup schematics of the PIC-based SD-OCT system with an on-chip coupler and arrayed waveguide grating (AWG), and in vivo tomograms and three-dimensional rendering, respectively of human skin (×32 averaged). Adapted with permission [77]. © The Optical Society (C) Common path OCT setup sketch with integrated microball lens, A-scan and tomograms of a three-layered phantom. Adapted with permission [89]. © The Optical Society. (D) Sketch of the on-chip receiver, pictures of the fabricated PIC and in vivo tomograms of human lip. Reproduced with permission [88]. © The Optical Society
Two articles reported on parallelized sample arms [75, 90]. The very first demonstration of PIC-based OCT used eight parallel Michelson interferometers for TD-OCT. The PIC was mounted on a three-axis translational stage for scanning and in vivo tomograms of a human fingertip were presented. With an axial resolution of 5.5 μm and 100 dB sensitivity the main drawback was the limited imaging speed of the TD-OCT system. The second approach of parallelized sample arms was demonstrated in 2017 [90]. A three-layer cascade of 1 x 2 splitters was integrated, resulting in eight parallel imaging beams. These beams have an optical delay of 3.7 mm, resulting in a time division multiplexed interference. The imaging speed therefore increases by the number of parallel channels resulting in an effective A-scan rate of 800 kHz using a 100 kHz light source. A system sensitivity of 91 dB and 100 kHz light source. A system sensitivity of 91 dB and an axial resolution of 8.3 μm at a central wavelength of 1310 nm were achieved. However, the signal of all eight channels is recombined and sent to one photo diode, which increases background noise, due to missing dual balanced detection. Nevertheless, this system demonstrates one of the main advantages of PIC-based OCT: significantly increasing the imaging speed by parallelization while maintaining good imaging sensitivity. A low-loss routing concept of a PIC-based multi-channel OCT system was proposed in [99] and is discussed in more detail in the next section.

One article reports on a PIC-based receiver for SS-OCT as shown in Figure 5D [88]. The receiver enables full-range OCT, polarization diversity detection and polarization-sensitive OCT. External photonic components like couplers were still used to complete the OCT system.

The above-described systems only involve individual PIC-based components. Four out of the 16 articles co-integrated photonic and electronic parts, making these systems the most mature ones in PIC-based OCT. One step towards a fully integrated PIC-based OCT shows a system with integrated receiver and interferometer on one silicon chip, leaving only the swept-source external [81, 107]. Starting with a single on-chip germanium photodiode connected to an interferometer, the system was later-on improved by including two photodiodes allowing dual balance detection. For the improved receiver, two OCT systems were presented, one with an integrated reference path and one with an external reference path of variable length. This allows scanning with galvanometric mirrors in the sample arm. In the system with the internal reference path, light was edge coupled into the chip with a lensed fiber. The spot size in the focus of the lensed fiber was matched to the mode field diameter of the waveguide tapers to reduce the coupling losses achieving an overall sensitivity of 53 dB. In the system with the external reference arm additional micro-lenses were printed on the chip facet with laser lithography to increase the coupling efficiency. The minimal loss between a lensed port and single-mode fiber was $-4$ dB over a 100 nm wavelength span. A system sensitivity of 64 dB was measured.

Further integration is shown by co-packaging a MEMS mirror with a PIC-based interferometer for SS-OCT and photodiodes (Figure 6A) [92]. The MEMS mirror allows for a smaller footprint and scanning with an A-scan rate of 100 kHz. With this packaged OCT head, leaving only the swept-source laser external, a sensitivity of 90 dB at 500 μW power on the sample could be achieved. In vivo 3D imaging of a fingertip was shown. In the improved system [93], also the k-clock interferometer for sweep control of the swept-source was included on the chip. This is the first step towards the integration of a butterfly packaged laser source that normally relies on external electronics and an external k-clock. Nokia Bell Labs published a picture of a fully packaged PIC-based system in [108]. The first fully packaged OCT system was shown by Sancho-Dura et al. [94], as can be seen in Figure 6B. They presented a handheld, battery driven multimodal imaging system including an OCT engine and a digital epiluminescent microscope within a volume of 30 cm$^3$. The OCT engine with a thermo-optic variable delay line and a multiplexed multiple path reference arm is fully encapsulated in a butterfly package. A MEMS mirror is used for lateral scanning. With an A-scan rate of 1.7 kHz, a sensitivity of 93 dB could be achieved. Although imaging with up to 24 kHz is possible, the higher speed reduces the system sensitivity to 81.5 dB. The device is packaged in a tablet format with a handheld probe and weighs only 3 kg. As a system validation, tomograms of fingers of healthy volunteers as well as of pathologies are depicted. The system was commercialized by DermaLumics [79].

### 3.2.2 | PIC-based OCT for the 800 nm region

Only 24% or five out of 21 systems report on the development of PIC-based OCT systems suitable for retinal imaging (800 nm). Four of these systems report on AWGs for SD-OCT and one article reports on an MZI for SS-OCT. Akca et al. [80] showed measurements using an AWG at a wavelength region of 800 nm in 2012 [80]. With 125 output channels, they achieved an axial resolution of 25 μm and measured a system sensitivity of 75 dB. Ruis et al. [95] reported on a 512 channel AWG and an on-chip 50/50 coupler for ophthalmic application with an axial resolution of 5.9 μm. The system sensitivity was measured to be 77 dB and they showed a B-scan of a three-layered phantom (20 times averaged).
The first in vivo retinal imaging using PIC-based OCT was demonstrated recently [78]. Figure 7A shows the PIC with two AWGs with a footprint of $2 \times 2 \text{ cm}^2$ in comparison to a one-Euro coin. Two different AWG designs were investigated. Both have 256 output channels and support a bandwidth of 22 and 48 nm, respectively. With a fiber-based interferometer, sensitivities of 88–91 dB were achieved and axial resolutions of approximately 11 and 6.5 μm (in tissue) were measured using the small and large bandwidth AWG, respectively. With these systems in vivo retinal imaging on healthy subjects was performed, producing B-scans and 3D data as well as OCT-angiography. The losses through AWGs were approximately −16 and −12 dB, respectively, which points out the challenge of designing and fabricating high channel, low-loss AWGs. An overview of imaging performance using these setups in comparison to a commercial device (Carl Zeiss Cirrus 4000) is shown in Figure 7A.

SS-OCT on a PIC is in principle less demanding in terms of PIC design as the interfered light is detected via a pair of photodiodes and the spectral resolution is achieved by sweeping a narrow bandwidth line across a broad spectrum. The first imaging performance of an on-chip interferometer, designed for ophthalmic application was presented in [98, 99]. Figure 7B summarizes the current imaging performance of the on-chip interferometer SS-OCT system [97]. With eye safe laser powers (750 μW), a system sensitivity of 94 dB and an axial resolution of 5.5 μm were measured. Insertion losses, including propagation, building blocks and fiber to PIC coupling losses, amounted approximately 3.4 dB in case one fiber-PIC coupling event was involved and approximately 6.7 dB when two fiber-PIC coupling events were part of the measurement. The overall losses therefore seem to be dominated by coupling losses. The first in vivo retinal imaging using PIC-based SS-OCT is demonstrated in Figure 7B.

While it has been demonstrated that on-chip interferometer and AWGs can be used to replace individual components of an ophthalmic OCT system, a fully miniaturized ophthalmic PIC-based OCT has not been demonstrated yet. However, a low-loss routing concept for a multi-channel OCT system has been proposed recently [99]. The concept describes a system with four parallel sample arms and four individual photodiode pairs for dual balanced detection. Using polarization beam splitters rather than couplers a low loss routing can be achieved. Such a routing scheme increases the effective A-scan rate without sacrificing sensitivity compared to a standard single channel system. Another interesting concept using PICs to overcome the traditional speed limitations of OCT techniques has been proposed in an MR-
TD-OCT configuration [109]. By sequentially tapping out the reference and sample arm lights at multiple locations using electro optical switches, the speed limitations of TD-OCT could be overcome on a chip-scale. Finally, a cooperation between NASA and Acucela, Inc., is focusing on a miniaturized OCT device to monitor retinal changes of astronauts exposed to micro gravity, including patents [110–112].

4 | CONCLUSION

The three identified approaches to miniaturize OCT have been evaluated in terms of imaging performance and compactness: Handheld probes, that is, sample arms that are decoupled from a (mobile) base station show good imaging performance, while the miniaturization and/or mobility are limited. Home/self-OCT systems impress with very compact and mature complete systems, while a reduced imaging performance can generally be observed.

PIC-based OCT technology, especially for ophthalmic application, is still in its infancies. Three articles, and four systems, respectively in the wavelength region >1100 nm demonstrated co-packaged or co-integrated systems. One of these systems was commercialized by DermaLumics and one system seems on the horizon of being commercialized by Nokia Bell labs. In the wavelength region <1100 nm, that is, for ophthalmic imaging, the usage of only individual subcomponents has been shown and first in vivo retinal imaging was demonstrated very recently.

In general, PICs gained more importance in the recent years, as they have the potential to integrate complex systems to a high degree in a small form factor and low cost of goods. This gives PICs the advantage of a high precision, scalable and cost-efficient fabrication technology. Still, many different aspects have to be considered, when designing and fabricating a PIC, most importantly the choice of material and the integration of the PIC into the OCT system. Certain challenges, such as a lossless connection from PIC to non-PIC components have to be solved. Therefore, expertise in many different research fields is needed. This is a limiting factor for the development of PIC-based OCT and might explain the limited amount of PIC-based OCT articles although this technique is of high scientific as well as economic interest.
A compact, handheld and cost-effective OCT system would open new markets, such as for general practices, in low-resource settings and homecare. Even applications in space flight could profit from such developments. With the outbreak of the Covid-19 pandemic in 2020 and the need to reduce social interaction, non-urgent medical appointments were canceled and postponed. To counteract a reduced medical care the use of tele-medicine was promoted and rapidly implemented whenever possible [113, 114]. These developments further encourage the search for a truly miniaturized, handheld OCT system. As we have seen giant leaps in the miniaturization in nearly all areas of electronic developments, further studies will pave the way to mirror these developments in the field of PIC.

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CONFLICT OF INTERESTS
Wolfgang Drexler is a paid consultant for Carl Zeiss Meditec, Inc., Dublin, CA, USA. Tilman Schmoll is an employee of Carl Zeiss Meditec, Inc., Dublin, CA, USA. The other authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT
Data are available in article supplementary material.

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