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REVIEW ARTICLE

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Silicon optical fibres – past, present, and future

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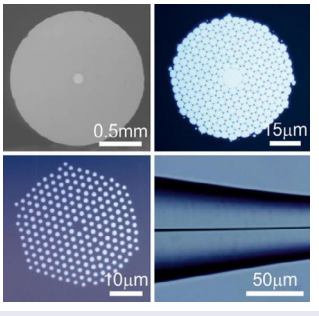
ABSTRACT

This paper reviews the past, present and prospective future of silicon optical fibres. The incorporation of silicon with its rich optoelectronic functionality into existing glass fibre technologies presents a route to controlling and manipulating the transmitted light in an unprecedented manner – opening the door to new and wide-ranging applications. Currently, there are two main fabrication approaches to producing these fibres – one involving chemical deposition inside glass capillary templates and the other a more traditional drawing tower technique starting from a rod-in-tube preform – each of which offers different advantages in terms of the material, geometry and waveguiding properties. As 2016 represents the 10th anniversary of the first silicon optical fibre, it is timely to evaluate and speculate on the future of this technology – in all its forms.



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Historical overview

One particular beauty of optical fibre is its enabling qualities. Fibres serve both as a test-tube for fundamental science and as a tool for practical applications.

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Though anecdotal, approximately every decade, the field enjoys a discovery that opens new doors: low loss silica fibres in the 1970s [1], optical amplifiers (Raman in the 1970s [2] and erbium-doped fibre amplifiers in the 1980s [3]) and photonic crystal fibres (PCFs) in the 1990s [4]. In the mid-2000s, glass-clad optical fibres that possessed cores of crystalline and amorphous semiconductors were developed and a global effort began to explore new compositions, to understand and control the underlying optical and materials science, and to make practical and useful devices from them. The focus of this Review is on a particular subset of these fibres that possess a silicon core, which are showing great promise for both optical and optoelectronic applications. However, for completeness, it is noted that the fabrication of bare silicon fibres dates back to the 1990s when they were grown via micro-pull-down methods [5].

The initial breakthrough in this field came in 2006 when a team of researchers from the United States (US) and the United Kingdom (UK) published their work on the fabrication of glass-clad silicon optical fibres using chemical vapour deposition (CVD) inside pre-existing silica capillaries [6]. It did not take long for the optical properties of these fibres to be studied and applied [7]. A second breakthrough came shortly thereafter when a scalable method, called the molten core (MC) approach, was adapted by another US team to fabricate long lengths of glass-clad silicon core fibres [8]. This approach is now more commonly employed globally and signals the potential for silicon core fibres to eventually move from the university laboratory, into wider scale availability and use.

To this end, Figure 1(a) shows the growth by year in peer-reviewed journal publications and citations on optical fibres fabricated from semiconductor materials. Figure 1(b) breaks down this information by geographic region. The data for both were collected based on the two foundational publications [6,8] and the subsequent citation tree that resulted. By the time of the printing of this Review, nearly 100 journal articles relating to semiconductor optical fibres will be in the peer-reviewed literature, those having been cited well over 1600 times. Two initial trends are clear. Firstly, following the pioneering efforts, after scholars had time to

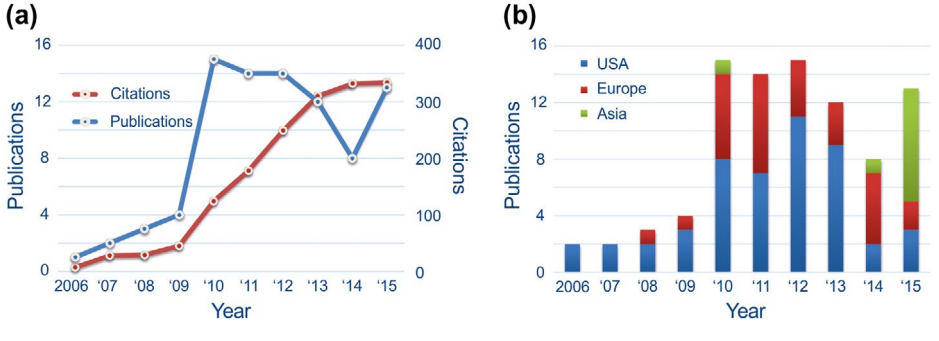

Figure 1. Progression in time of (a) the semiconductor optical fibre journal publications and citations and (b) the geographic region of the corresponding author on said publications.

fabricate their own fibres and conduct preliminary measurements, a rapid growth in publications ensued (2009–2010). The publication rate then remained fairly constant over the next few years, followed by a relative lull while groups considered the next advancements (2013–2014). However, the field has since returned to a growth mode (2015), which is promising for future developments. The second trend is more geographical in that, while the US and Europe remain the larger regions from which scholarly works on semiconductor fibres originate, Asia is greatly growing their efforts and has (in 2015) overtaken both other regions combined. In musing about the future, it is not difficult to envision continued growth in publications and regional diversity, though there remain a series of barriers to performance that tend to limit more expansive growth of their applications. In particular, if the silicon optical fibres are to move beyond a mere research curiosity and into the industrial market, the most important hurdle to overcome is reducing the fibre attenuation.

This Review aims to summarize the first 10 years of the silicon optical fibre technology, the present status of its development and performance, prospective applications and opportunities for improvement. There are several quality reviews available for the interested reader that discuss the broader range of semiconductor optical fibres, including those made from other unary and binary core phases [9–11]. However, owing to the global interest in silicon photonics [12], it is the silicon core materials that have been the most widely studied and applied. The ultimate motivation for these efforts is to use the silicon optical fibre technology to unite the benefits of the highly functional silicon materials with the fibre infrastructures capable of confining and controlling light over long distances. The sections that follow detail the main fabrication processes for glass-clad silicon optical fibres, their comparative advantages and disadvantages, the performance of the resultant fibres, and present and emerging applications. The Review concludes with perspectives on the future, including topics where continued efforts are needed.

Fabrication procedure

Interestingly, although both the aforementioned foundational CVD and MC approaches to silicon optical fibre fabrication were developed to be (and are in practice) much more broadly applicable to other crystalline and glass systems, the greatest progress has been made in relation to the silica clad, silicon core fibres. As previously mentioned, the first silicon optical fibres were fabricated using a high-pressure chemical vapour deposition (HPCVD) method to incorporate the semiconductor material inside the hollow channels of silica capillaries and PCFs [6]. Though the CVD of silicon has been widely employed, the novelty in this work was the application of that technology at higher pressures on to (or, rather, inside) a non-planar surface such as a capillary fibre. Such high pressures are crucial to help overcome the mass transport constraints, allowing for the chemical precursors to flow down the lengths of the high aspect ratio pores. Importantly,

as the surfaces of the pre-drawn silica capillaries are atomically smooth, they offer a pristine surface on which to deposit and ripen the silicon materials. It is worth noting that as the deposition temperatures can be either above, or below the temperature required to nucleate and grow crystalline grains, the process is uniquely amendable to both crystalline and amorphous semiconductors [7,13].

The molten core method, which has been more widely employed to the fabrication of several types of semiconductor optical fibres, originated from the powder-in-tube approach conceived for the realization of optical fibres from otherwise unstable glasses [14]. The underlying premise is a simple one, though the reduction to practice in some cases is not. In general, a core phase, which can be particulate or bulk, crystalline, polycrystalline or even amorphous, is sleeved inside a glass cladding tube whose bottom end has been sealed. As the name suggests, the core phase is molten at the draw temperature of the cladding glass. Thus, the cladding acts as a crucible that both contains the core material as it melts and serves as the cladding for the resultant optical fibre upon drawing. As such, there is no need for CVD processes as in conventional silica optical fibre fabrication, or indeed as above; only a draw tower or thermal pulling source is needed. For example, silicon optical fibres have also been made using laboratory scale, custom-made thermal drawing systems [15,16]. Regardless of the heating and drawing setup employed, thus far the liquid silicon cores have always solidified into a (poly) crystalline phase upon cooling, though there are somewhat competing theories as to whether or not "bulk" (i.e. cooled from melt) amorphous silicon is possible [17,18]. Given the cooling rates experienced by the silicon melt in the molten core fibres, the realization of long lengths of amorphous silicon optical fibre remains a possibility worth further exploration.

It is worth noting that the MC approach is, in practice, considerably more complicated than its general description suggests, presenting both opportunities and challenges. Principal among these are the interaction products that result between the core melt and softened cladding glass. The canonical problem for the MC approach is oxide contamination of the silicon core by dissolution of the silica cladding. In the original work, this amounted to about 17 atom per cent oxygen, which dominated the measured losses [8]. The HPCVD process tends not to suffer from such dissolution issues because the process is low temperature by comparison. That said, the thermal activity necessarily associated with the high temperatures inherent to the molten core process have been used as an advantage to make the fibre draw process itself "reactive". In these cases, chemistry is performed *in situ* during the draw such that the core of the fibre can be quite different in composition from what it was in the preform. Insightful examples of this include the oxygen-free silicon core fibres obtained by using SiC in the melt [19], or by placing alkaline earth modifiers at the core/cladding interface [16]. However, perhaps more remarkable are the silicon optical fibres drawn from a preform with an aluminium core and silica cladding. In this latter case, the redox

reaction between aluminium and silica is employed during the draw to realize a fibre with an entirely different core composition than that of the originating preform [20].

As with any fabrication method, advantages and disadvantages exist for each. The HPCVD approach permits the fabrication of fibres with very small cores (few microns in diameter), of both crystalline and amorphous phases, as well as complex two-dimensional photonic crystal designs that can be exploited to precisely control the waveguiding properties. Moreover, and perhaps even of greater benefit, multiple materials can be deposited within the capillary pores layer-by-layer, permitting the in-fibre fabrication of optoelectronic junctions [21,22], which will be discussed in more detail below. The main drawback of this approach is that it produces fibres of limited lengths, typically on the order of a few centimetres of uniform material. In contrast, the MC approach allows for very long (kilometre) lengths of fibre to be drawn with a uniform cross-section, though initial fibres were restricted to large (hundreds of micron) core sizes due to oxygen contamination. More recently the challenge of obtaining small, high purity cores that are more typical for fibre geometries has been addressed via the incorporation of interfacial modifiers [16]. Though not as easily formed as with HPCVD, in-fibre p-n junctions have also been realized in molten core derived fibres [23].

Figure 2 shows the year-on-year progress in the development of both the HPCVD and molten core silicon core fibres in terms of their attenuation losses in the telecom band [6–8,13,16,24–27]. To date, the lowest loss reported in this platform (for this wavelength region) was measured in a hydrogenated amorphous silicon (a-Si:H) HPCVD fibre. In this specific case, the incorporation of hydrogen

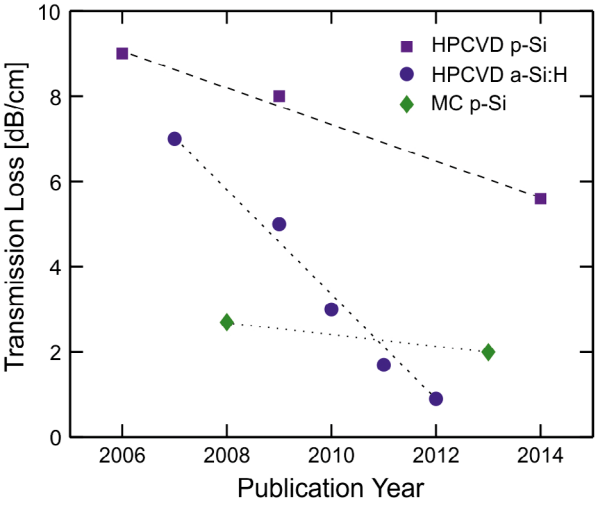

Figure 2. Year-on-year progress to reduce the losses in the silicon optical fibres fabricated by both the molten core (MC) and HPCVD approaches; dashed lines simply are a guide for the eye. Notes: Values are plotted for fibres both with polysilicon and hydrogenated amorphous silicon core materials, taken from the references: [6–8,13,16,24–27].

was critical to obtaining such low losses as it passivates the dangling bonds, which are otherwise a significant source of absorption in this disordered material. The steady reduction in losses shown here has been attributed to an improvement in controlling the concentration and distribution of hydrogen throughout the core. In contrast, the primary source of loss in the polysilicon (p-Si) core fibres is most likely due to impurities and defects situated at the grain boundaries. It is worth noting that the fact that the losses in the molten core p-Si fibres started off low, and have stayed low, is indicative of the very large crystal grains produced via this method. However, for both approaches, the lowest measured losses are on the order of 1–2 dB/cm, which is not far from those reported for planar silicon waveguides (amorphous or crystalline). In the case of planar waveguides, the losses tend to be dominated by surface roughness, whereas this is not the case in the silicon core fibres, given the very low roughness of the silica cladding tube. Accordingly, the aforementioned bulk defects (and quite probably some additional unidentified extrinsic factors) are limiting continued progress towards lower losses. Whatever the sources, reducing the attenuation of the silicon optical fibres to ~1 dB/m, or less, represents one of the greatest opportunities for continued development and would open up considerable doors for practical applications.

Unlike conventional glass optical fibres or planar semiconductor waveguides, there is substantial post-processing that can be (though not necessarily is) done to further influence the properties and performance of the silicon optical fibres. Marked improvements in single crystallinity and preferential crystallographic orientations have been observed in thermally [28] and laser-annealed silicon optical fibres [27], with the latter result producing the lowest loss HPCVD p-Si fibre in Figure 2. Further to this, silicon core fibres can be tapered at temperatures above the melting point of the silicon, but where the silica cladding glass can still be controllably deformed. As well as allowing for precise tailoring of the core size [29], this tapering process has also been shown to enhance and control the crystallographic orientation of the silicon with respect to the fibre axis [30,31]. While not necessarily germane to cubic silicon, crystallographic control would be of great value to non-cubic, hence potentially $\chi^{(2)}$-active semiconductor core phases. More recent work on using controlled capillary instabilities to produce silicon-in-silica microspheres [32] and microspherical resonators [33] has provided an additional degree of flexibility to tailor the optical confinement, broadening the scope of the applications.

Recent advances and emerging applications

Although continued development is required, and being done, as regard to the fabrication in order to unlock the full optoelectronic potential of these fibres, some useful device demonstrators have been reported. Importantly, these have allowed the silicon fibres to be benchmarked against their more conventional counterparts,

establishing their viability in application areas that range from nonlinear processing to sensing and photovoltaics.

Optical fibres

Figure 3 presents a pictorial overview of the silicon optical fibre geometries that have been investigated for photonic device development. To date, most of the advances in this area have employed step index fibres (Figure 3(a)), where the lowest transmission losses, typically a few dB/cm, have been obtained (see Figure 2). The potential applications for these fibres are very much dependent on their dimensions, with the large core fibres showing promise for infrared power delivery [8,11] and the smaller core fibres of use for nonlinear signal processing, where their performances have been shown to rival their nanoscale counterparts on-chip [34]. However, one of the drawbacks of the high core/cladding index contrast is that these step index fibres have a very high numerical aperture and thus support a large number of modes, which can degrade the device performance [35]. A route to circumventing this problem is to make use of existing silica PCFs as two-dimensional templates into which the silicon materials are deposited via the HPCVD approach. In addition to reducing the number of guided modes, these novel fibre designs can also be used to improve integration with conventional glass-based fibres, either through better matching of the mode areas (Figure 3(b) [36]) or core materials (Figure 3(c) [37]). In the case of Figure 3(c) where the core

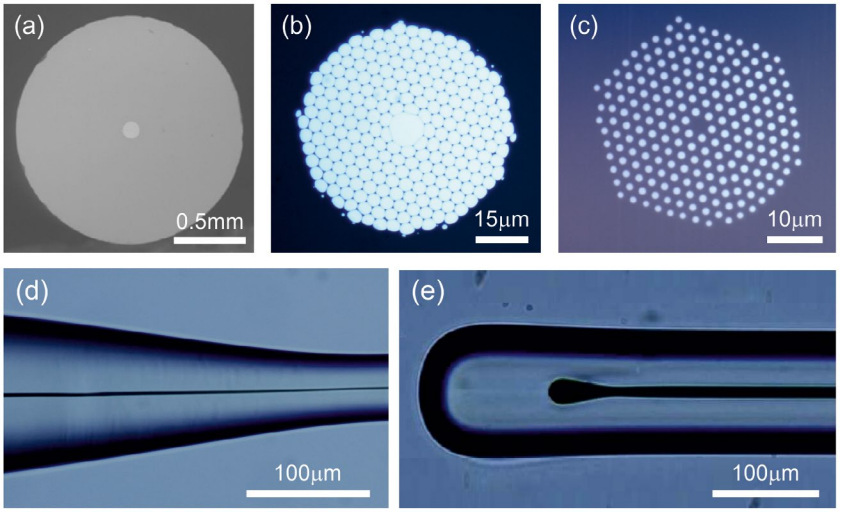

Figure 3. An assortment of silicon optical fibres.
Notes: Microscope images of (a) a molten core derived step index fibre, and two HPCVD fabricated PCFs where (b) is an index guiding silicon core fibre and (c) is a bandgap guiding silica core fibre. Post-processed silicon fibres where in (d) the core is tapered longitudinally and (e) it is shaped to form a microspherical resonator at the end.

is silica and the silicon is a high index inclusion in the cladding, the fibre guides via a bandgap mechanism, which also allows for extreme dispersion tailoring of the guided modes. The tapered fibres described earlier (depicted in Figure 3(d)), provide a further means to control the dispersion and the nonlinearity through the varying core dimensions. For example, using this procedure, fibres have been fabricated with the submicron core sizes required to access the anomalous dispersion regime [29], which is important for nonlinear processes such as soliton formation [38] and supercontinuum generation [39]. Additional enhancements in the nonlinear performance have been achieved using the shaped microspherical resonators (Figure 3(e)), owing to their small mode volumes and high-quality factors, on the order of $Q{\sim}10^5$ [33,40]. All-optical modulation has been demonstrated in these resonators using both the slow thermo-optic [41] and ultrafast Kerr [42] nonlinearities, for incident power levels that are significantly lower (up to four orders of magnitude) than previous transmission-based experiments [34].

Optoelectronic fibres

Several optoelectronic effects have been demonstrated in fibres made both via the molten core and HPCVD methods. Although the HPCVD materials are most typically deposited in an amorphous form, they can be thermally annealed to obtain the crystalline quality required for efficient charge transport [13]. A key advantage of this fabrication approach is that coaxial homo and hetero-junctions can be realized by sequentially changing the gas composition during deposition, in an analogous way to how core/clad profiles are established in conventional silica-based glass fibres. In this junction geometry, the interaction length of the light propagating down the axis is decoupled from the carrier collection path, which occurs radially, allowing for the construction of high-efficiency and high-speed devices such as photodetectors [21] and electrically driven modulators [22]. In contrast, while devices made from the molten core fibres benefit from the superior purity and crystallinity of the core materials, in general further processing is required to introduce additional active material layers. Figure 4 shows two different arrangements that have been investigated for photovoltaic conversion: (a) the vertical rod geometry [43], where the glass cladding is partially etched to expose the core; and (b) a horizontal rod geometry [44], where the silicon is completely removed from the cladding and assembled into an array. In both cases, the etched silicon fibre substrates, doped or not, are subsequently coated to form the junction device. Compared to planar structures, these fibre-based platforms can offer increased absorption over a wider range of angles and wavelengths, per unit silicon volume [44]. It is interesting to note that the purity of the silicon (initially 99.98%) was increased by the fibre drawing process due to impurity segregation to the interface and grain boundaries [45]. This approach, where the silicon is formed into the desired thickness and shape in a single step, reduces the energy required for crystallization and largely eliminates the material losses associated

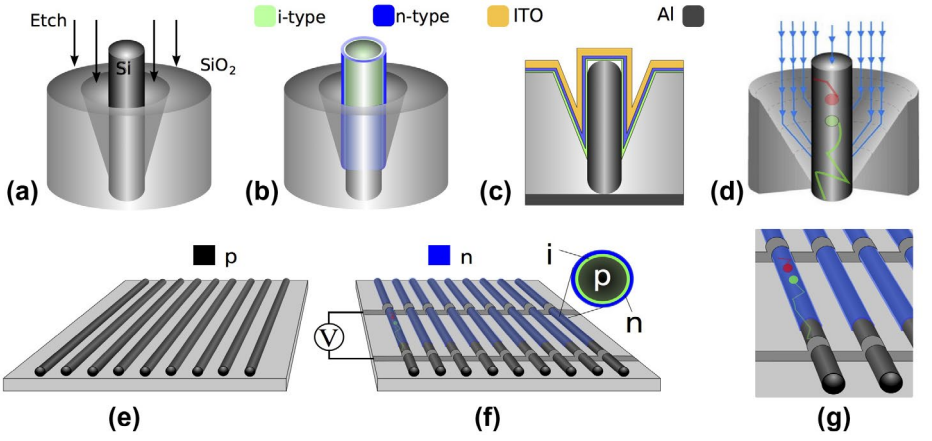

Figure 4. Fabrication of vertical (a–d) and horizontal (e–g) solar cells based on silicon fibres. Majority carrier collection is down the central core to the aluminium, while minority carriers are extracted to the indium tin oxide contact radially (d and g).

with boule and wafer sawing. The ability to draw long continuous filaments suggests that an in-line processing path could be developed to make high-efficiency solar cells with reduced cost.

Perspectives and outlook

As has just been described, over their first 10 years, silicon fibres have emerged from an oddity to candidates for use in all-optical and optoelectronic devices. What is on the horizon?

Integrated systems

One of the key advantages of fibre systems is their potential to be seamlessly linked together into compact and robust systems. However, there are a number of challenges facing the integration of silicon core fibres with the more conventional glass structures owing to the differences in the material properties. Preliminary efforts in this area have shown that robust and distortion-free fusion splicing between these two systems is possible using a "cold" splicing technique (Figure 5(a)), though further work is required to reduce the connection losses [46]. One promising solution would be to first taper the silicon core to better match the mode index and size of the glass fibres, as in Figure 3(d), in an approach analogous to the inverse taper designs employed by the planar community. Importantly, these tapered silicon fibres could also be used to improve coupling to the nanoscale waveguides favoured on chip, thus providing a simple route to robust and broadband fibre-to-chip coupling.

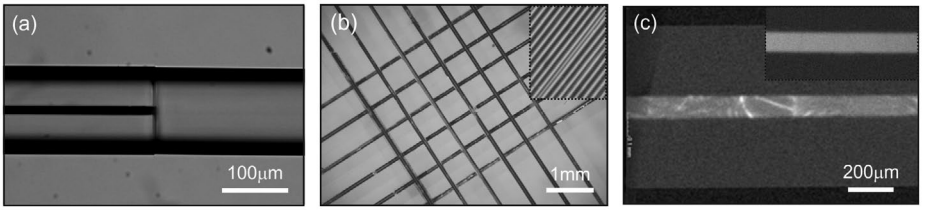

Figure 5. (a) Splicing of a silicon fibre to a conventional silica fibre. (b) A silicon fibre mesh (inset: dense stacking of silicon fibres). (c) X-ray tomography slice partway through a $Si_{0.94}Ge_{0.06}$ alloy fibre showing composition fluctuations (inset: the uniform SiGe core after laser processing).

Medical applications

As the optical quality of the silicon core material improves, these fibres are emerging as excellent candidates for medical applications that rely on the delivery and collection of mid-infrared radiation from surgical lasers, such as Er:YAG. In contrast to many of its competitors (e.g. the chalcogenides), silicon is biocompatible, non-toxic and can withstand high-temperature industrial processes. Moreover, as improved optical sources with increasingly longer wavelengths become available, the transmission limits of the fluoride glass and sapphire fibres currently in use today will be exceeded. Thus, we anticipate that robust and stable mid-infrared silicon optical fibres could play a significant role in the development of future health care systems.

Electronic fibres

Investigations of the electronic properties of silicon fibres have revealed a number of favourable properties for device applications. In particular, partly due to the extraordinary large grain sizes of the molten core fibres (up to ~1–2 cm in length), their majority carrier mobility can be comparable to single crystal wafers [45], with a resistivity that reflects the level of dopants in the starting material [47]. As previously discussed, fibre-based junctions fabricated from doped coaxial layers are already showing great promise for photo-detection. However, recent results have also shown that it is possible to tune the electronic bandgap of the silicon fibre core material using a selective laser heating process that induces a large strain between the confined core material and cladding [27]. Importantly, this process is highly localized (to the laser focus point) so that it opens a route to "writing" junctions and other electronic functions in to the fibres precisely where they are needed, at any point along the length. We anticipate that eventually such electronic fibres could be woven into smart textiles, along the lines of Figure 5(b), for use as wearable solar cells, position sensors and health monitors.

Alloy and compound fibres

Although this article has focused on the single element silicon fibres, the potential of this platform expands rapidly when considering alloy or compound core fibres. To date, fibres have been fabricated with a variety of core materials, including germanium [48], tellurium [49], zinc selenide (II-VI) [50], indium antimonide (III-V) [51] and SiGe alloys [52]. It should be mentioned that the SiGe material system is of growing interest to the photonics community as it is possible to tune the optoelectronic properties (through the composition) to match the target application – which could be anything from light emission, to modulation and optical detection. So far the as-drawn SiGe fibres have shown large fluctuations in their composition, as in Figure 5(c) [52], which will be associated with variations in the local bandgap and refractive index. This could be exploited to improve the thermoelectric properties [53], or microwire solar cell performance [54], due to increased scatter and current collection. Alternatively, laser processing can be employed to homogenize the composition, as shown in the inset of Figure 5(c). Additional opportunities will also be realized with further improvements to the group II–VI and III–V materials, which, in combination with transition metal dopants [50] or rare earth ions [55], could constitute the active gain element in miniature mid-infrared lasers. Indeed, a proof of concept semiconductor fibre laser has recently been reported [56]. For all fibres, detailed studies to determine and eliminate the sources of transmission loss are critical goals for the coming years.

Concluding remarks

The current growth and diversification of research groups involved in the fabrication and testing of the silicon optical fibres is a clear indication that this technology is starting to come of age. Over the forthcoming years, we can expect to see increasingly more innovative processing procedures being pursued and developed, resulting in reduced losses and longer usable fibre lengths that will ultimately stimulate new research directions and applications. Although we do not expect these fibres to replace their pure silica counterparts, they will certainly add more functionality and spice to the existing array of fibre components.

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References

[1] D.B. Keck and A.R. Tynes, Appl. Opt. 11 (1972) pp. 1502–1506.
[2] R.H. Stolen and E.P. Ippen, Appl. Phys. Lett. 22 (1973) pp. 276–278.
[3] R.J. Mears, L. Reekie S.B. Poole and D.N. Payne, Electron. Lett. 22 (1986) pp. 159–160.
[4] J.C. Knight, T.A. Birks, P. St. J. Russell and D.M. Atkin, Opt. Lett. 21 (1996) pp. 1547–1549.
[5] K. Shimamura, S. Uda, T. Yamada, S. Sakaguchi and T. Fukuda, Jpn. J. Appl. Phys. 35 (1996) pp. L793–L795.
[6] P.J.A. Sazio, A. Amezcua-Correa, C.E. Finlayson, J.R. Hayes, T.J. Scheidemantel, N.F. Baril, B.R. Jackson, D.-J. Won, F. Zhang, E.R. Margine, V. Gopalan, V.H. Crespi and J.V. Badding, Science 311 (2006) pp. 1583–1586.
[7] D.-J. Won, M.O. Ramirez, H. Kang, V. Gopalan, N.F. Baril, J. Calkins, J.V. Badding and P.J.A. Sazio, Appl. Phys. Lett. 91 (2007) p.161112.
[8] J. Ballato, T. Hawkins, P. Foy, R. Stolen, B. Kokuoz, M. Ellison, C. McMillen, J. Reppert, A.M. Rao, M. Daw, S. Sharma, R. Shori, O. Stafsudd, R.R. Rice and D.R. Powers, Opt. Express 16 (2008) pp. 18675–18683.
[9] J. Ballato, T. Hawkins, P. Foy, B. Yazgan-Kokuoz, C. McMillen, L. Burka, S. Morris, R. Stolen and R. Rice, Opt. Fiber Technol. 16 (2010) pp. 399–408.
[10] A.C. Peacock, J.R. Sparks and N. Healy, Laser Photonics Rev. 8 (2014) pp. 53–72.
[11] G. Tao, H. Ebendorff-Heidepriem, A.M. Stolyarov, S. Danto, J.V. Badding, Y. Fink, J. Ballato and A.F. Abouraddy, Adv. Optic. Photonics 7 (2015) pp. 379–458.
[12] B. Jalali and S. Fathpour, J. Lightwave Technol. 24 (2006) pp. 4600–4615.
[13] L. Lagonigro, N. Healy, J.R. Sparks, N.F. Baril, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Appl. Phys. Lett. 96 (2010) p.041105.
[14] J. Ballato and E. Snitzer, Appl. Opt. 34 (1995) pp. 6848–6854.
[15] B. Scott, K. Wang and G. Pickrell, IEEE Photonics Technol. Lett. 21 (2009) pp. 1798–1800.
[16] E. Nordstrand, A. Dibbs, A. Eraker and U.J. Gibson, Opt. Mater. Express 3 (2013) pp. 651–657.
[17] Y. Shao, F. Spaepen and D. Turnbull, Metall. Mater. Trans. A 29 (1998) pp. 1825–1828.
[18] H. Tanaka, Phys. Rev. B 66 (2002) p.064202.
[19] S. Morris, T. Hawkins, P. Foy, C. McMillen, J. Fan, L. Zhu, R. Stolen, R. Rice and J. Ballato, Opt. Mater. Express 1 (2011) pp. 1141–1149.
[20] C. Hou, X. Jia, L. Wei, S.-C. Tan, X. Zhao, J. Joannopoulos and Y. Fink, Nat. Comm. 6 (2015) p.6248.
[21] R. He, P.J.A. Sazio, A.C. Peacock, N. Healy, J.R. Sparks, M. Krishnamurthi, V. Gopalan and J.V. Badding, Nat. Photonics 6 (2012) pp. 174–179.
[22] R. He, T.D. Day, M. Krishnamurthi, J.R. Sparks, P.J.A. Sazio, V. Gopalan and J.V. Badding, Adv. Mater. 25 (2013) pp. 1461–1467.
[23] D. Homa, A. Cito, G. Pickrell, C. Hill and B. Scott, Appl. Phys. Lett. 105 (2014) p.122110.

[24] P. Mehta, N. Healy, N.F. Baril, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Opt. Express 18 (2010) pp. 16826–16831.
[25] P. Mehta, N. Healy, T. D. Day, J. R. Sparks, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Opt. Express 19 (2011) pp. 19078–19083.
[26] P. Mehta, N. Healy, T.D. Day, P.J.A. Sazio, J.V. Badding and A.C. Peacock, *Effect of Core Size on Nonlinear Transmission in Silicon Optical Fibers*, CLEO/QELS, San Jose, CA, 2012.
[27] N. Healy, S. Mailis, N. Bulgakova, P.J.A. Sazio, T. Day, J. Sparks, H. Cheng, J. Badding and A.C. Peacock, Nat. Mater. 13 (2014) pp. 1122–1127.
[28] N. Gupta, C. McMillen, R. Singh, R. Podila, A.M. Rao, T. Hawkins, P. Foy, S. Morris, R. Rice, K.F. Poole, L. Zhu and J. Ballato, J. Appl. Phys. 110 (2011) p.093107.
[29] N. Healy, J.R. Sparks, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Opt. Express 18 (2010) pp. 7596–7601.
[30] C. McMillen, G. Brambilla, S. Morris, T. Hawkins, P. Foy, N. Broderick, E. Koukharenko, R. Rice and J. Ballato, Opt. Mater. 35 (2012) pp. 93–96.
[31] S. Morris, C. McMillen, T. Hawkins, P. Foy, R. Stolen and J. Ballato, J. Crystal Growth 352 (2012) pp. 53–58.
[32] A. Gumennik, L. Wei, G. Lestoquoy, A.M. Stolyarov, X. Jia, P.H. Rekemeyer, M.J. Smith, X. Liang, B.J.B. Grena, S.G. Johnson, S. Gradečak, A.F. Abouraddy, J.D. Joannopoulos and Y. Fink, Nat. Comm. 4 (2013) pp. 2216–2220.
[33] F. Suhailin, N. Healy, Y. Franz, M. Sumetsky, J. Ballato, A.N. Dibbs, U.J. Gibson and A.C. Peacock, Opt. Express 23 (2015) pp. 17263–17268.
[34] P. Mehta, N. Healy, T.D. Day, J.V. Badding and A.C. Peacock, Opt. Express 20 (2012) pp. 26110–26116.
[35] A.C. Peacock, P. Mehta, P. Horak and N. Healy, Opt. Lett. 37 (2012) pp. 3351–3353.
[36] N. Healy, J.R. Sparks, M.N. Petrovich, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Opt. Express 17 (2009) pp. 18076–18082.
[37] N. Healy, J.R. Sparks, R.R. He, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Opt. Express 19 (2011) pp. 10979–10985.
[38] A.C. Peacock, Opt. Lett. 35 (2010) pp. 3697–3699.
[39] L. Shen, N. Healy, L. Xu, H. Cheng, T. Day, J.V.H. Price, J.V. Badding and A.C. Peacock, Opt. Lett. 39 (2014) pp. 5721–5724.
[40] C. Lin, J. Chen and L. Wang, IEEE Photonics Technol. Lett. 27 (2015) pp. 1355–1358.
[41] N. Vukovic, N. Healy, P. Mehta, T.D. Day, P.J.A. Sazio, J.V. Badding and A.C. Peacock, Appl. Phys. Lett. 100 (2012) p.181101.
[42] N. Vukovic, N. Healy, F.H. Suhailin, P. Mehta, T.D. Day, J.V. Badding and A.C. Peacock, Sci. Rep. 3 (2013) p.2885.
[43] F.A. Martinsen, B.K. Smeltzer, M. Nord, T. Hawkins, J. Ballato and U.J. Gibson, Sci. Rep. 4 (2014) p.6283.
[44] F.A. Martinsen, B. Smeltzer, J. Ballato, T. Hawkins, M. Jones and U.J. Gibson, Opt. Express 23 (2015) pp. A1463–A1471.
[45] F.A. Martinsen, J. Ballato, T. Hawkins and U.J. Gibson, APL Mater. 2 (2014) p.116108.
[46] L.M. Xiao, N. Healy, U. Gibson, T. Hawkins, M. Jones, J. Ballato and A.C. Peacock, *Fusion Splicing of Silicon Optical Fibres*, CLEO/Europe-EQEC, Munich, 2015.
[47] K. Ballato, *Electrical Characterization of Silicon Cores from Glass-Cladded Fibres*. MS Thesis, Norwegian University of Science and Technology, 2014.
[48] J. Ballato, T. Hawkins, P. Foy, B. Yazgan-Kokuoz, R. Stolen, C. McMillen, N.K. Hon, B. Jalali and R. Rice, Opt. Express 17 (2009) pp. 8029–8035.
[49] G. Tang, Q. Qian, X. Wen, G. Zhou, X. Chen, M. Sun, D. Chen and Z. Yang, J. Alloys Compd. 633 (2015) pp. 1–4.

[50] J. Sparks, R. He, N. Healy, M. Krishnamurthi, A.C. Peacock, P.J.A. Sazio, V. Gopalan and J.V. Badding, Adv. Mater. 23 (2011) pp. 1647–1651.
[51] J. Ballato, T. Hawkins, P. Foy, C. McMillen, L. Burka, J. Reppert, R. Podila, A.M. Rao and R.R. Rice, Opt. Express 18 (2010) pp. 4972–4979.
[52] D. Coucheron, *Rapid Directional Recrystallization of SiGe Fibres*. MS Thesis, Norwegian University of Science and Technology, 2015.
[53] C. Hou, X. Jia, L. Wei, A.M. Stolyarov, O. Shapira, J.D. Joannopoulos and Y. Fink, Nano Lett. 13 (2013) pp. 975–979.
[54] S.A. Healy and M.A. Green, Sol. Energy Mater. Sol. Cells 28 (1992) pp. 273–284.
[55] M. Zhang, A. Yang, Y. Peng, B. Zhang, H. Ren, W. Guo, Y. Yang, C. Zhai, Y. Wang, Z. Yang and D. Tang, Mater. Res. Bull. 70 (2015) pp. 55–59.
[56] A. Sandupatla, J. Flattery and P. Kornreich, Opt. Eng. 54 (2015) p.126113.