Integrated Microsphere Planar Lightwave Circuits

J.S. Wilkinson, G.S. Murugan, D.W. Hewak, M.N. Zervas, Y. Panitchob & G.R. Elliott
Optoelectronics Research Centre,
University of Southampton
Southampton, Hampshire, UK
jsw@orc.soton.ac.uk

P.N. Bartlett, E.J Tull & K.R. Ryan
School of Chemistry
University of Southampton
Southampton, Hampshire, UK
pnb@soton.ac.uk

Abstract—**Multicomponent glass microspheres self-assembled on optical waveguides combine tailored optical properties with strong light/material interaction potentially leading to compact low-power photonic devices. Progress and prospects for microsphere/waveguide integration will be described.**

Keywords:Integrated optics; optical resonators; self-assembly

I. Introduction

Resonant cavities are key components in photonic circuits, providing feedback, wavelength selectivity and energy storage to allow dispersion control and enhanced nonlinearity, resonant filtering, waveguiding with low bend radius and ultra-low threshold lasing. Silica microspheres and microcylinders with diameters ranging from a few microns to a hundred microns or more have been shown to exhibit high quality factors of order 10^9 when an appropriate whispering-gallery mode (WGM) is excited [1], and lend themselves to evanescent coupling to optical waveguides to provide integrated resonant functions in an optical circuit. Planar lightwave circuits (PLCs) can potentially offer low-cost mass-manufacturable solutions to complex optical circuit requirements, but conventional optical waveguide technology suffers from two problems which limit dense integration for multiple circuit functions. The first is that exploitation of many optical phenomena requires long optical path lengths to achieve, for example, sufficient delay in dispersion compensation, or sufficient growth of power in a nonlinear interaction. Coupling of waveguides to arrays of microresonators potentially allows energy storage, long delays and high-efficiency nonlinear interactions. The second problem is that, so far, no one material has emerged as ideal for photonic circuits, and microsphere integration with conventional waveguides allows flexible configuration of multiple materials systems. The most elegant demonstrations of microsphere resonators to date have employed light delivery by tapered optical fibres where the modes evanescently couple to WGMs of the spheres. Ultra-high Q microtoroid resonators based on silicon processing [2] exhibit excellent performance but are difficult to integrate directly in waveguide circuits, while photolithographically-defined ring resonators [3] and disk resonators [4] are limited in their materials flexibility. Planar lightwave circuits offer a platform for stable placement of microspheres or microsphere arrays, for example by self-assembly, along with evanescent coupling to single or multiple waveguides, to realise highly functional circuits in a more robust configuration than fibre devices, and with greater flexibility than monolithically integrated microresonators.

This work was funded by the UK EPSRC under grant GR/S96500/01

II. Glass Microspheres

High-quality unsupported microspheres were formed from exemplar multicomponent glasses with specific optical functionality. We have chosen Nd and Er-doped BK7 borosilicate glasses for their good laser and amplifier properties [5] and gallium lanthanum sulphide chalcogenide glasses for their high third-order nonlinearity for switching [6], and in both materials have obtained microspheres with (waveguide-coupled) loaded Q-factors >60,000, suitable for low-threshold lasing and high-bandwidth communications devices. Tellurite glass [7] microspheres have also been realised to exploit their excellent Raman gain properties. Microspheres of radius 15µm to 100µm were fabricated from crushed and sieved custom glass which was doped, purified and melted in our laboratories, by annealing in a specialised drop-furnace [8]. It was confirmed that the Nd-doped borosilicate and chalcogenide glass spheres lased when pumped with a focused free-space beam.

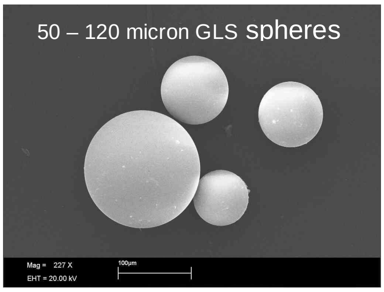

Figure 1. Gallium Lanthanum Sulphide glass microspheres

III. Microsphere Assembly

Most conventional self-assembly techniques are unsuitable for assembly of microspheres greater than about 5 microns in diameter, due to the reduced influence of convective forces [9]. A novel technique of selective chemical modification of structured substrates has been used to realise surfaces tailored to the assembly of glass microspheres from aqueous solution, allowing realisation of individual spheres in etched wells sparsely distributed over a substrate, as required for integrated microsphere planar lightwave circuits, and as shown in Figure 2, for 60µm diameter spheres in etched pits in borosilicate glass substrates [10]. The assembly process parameters have been studied in detail in terms of their influence on accuracy of positioning and defect density, to allow well-controlled construction of waveguide integrated devices.

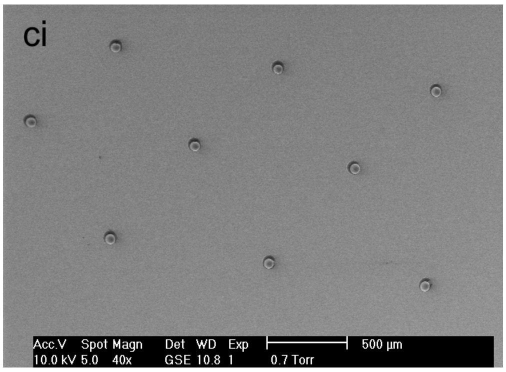

Figure 2. Glass microspheres assembled in pit array [10]

IV. MICROSPHERE-COUPLED WAVEGUIDES

Microspheres coupled to optical waveguides with variable separation have been characterised using both ion-exchanged glass waveguides [11] and tantalum pentoxide rib waveguides, the latter allowing a wide range of effective indices for phase-matching to WGMs in high-index spheres. Whispering-gallery mode spectra were obtained using a tunable line-narrowed source at wavelengths between 1440nm and 1640nm, and modes were assigned by fitting to sphere, waveguide and coupled-mode models. Typical data for a well-coupled microsphere (in this case Er-doped borosilicate glass) are shown in Figure 3, and mode-assignment allowed experimental confirmation of coupling coefficients, microsphere round-trip losses and WGM effective path lengths, enabling fine-tuning of device designs where the control of coupling coefficient through waveguide-microsphere separation is crucial. Controllable positioning of microspheres has also allowed the study of WGM mode-splitting in non-ideal microspheres, enabling determination of ellipticity and orientation.

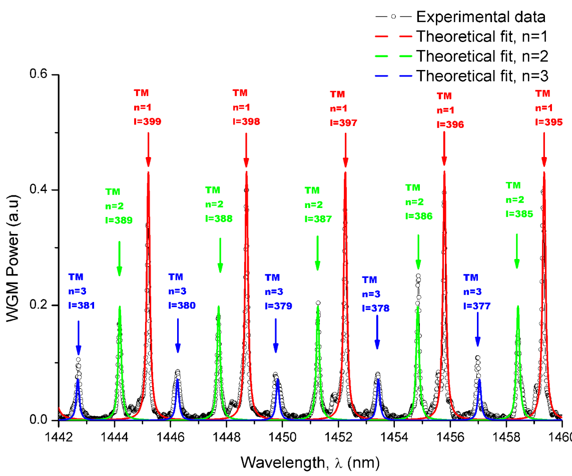

Figure 3. Typical WGM spectrum and mode-assignment.

Glass microspheres have been assembled between two otherwise uncoupled monomode Ta_2O_5 rib waveguides, as shown in Figure 4, with the aim of providing strongly wavelength-dependent coupling and to demonstrate nonlinear functionality. Arrays of microspheres may be readily formed on waveguide substrates and used to select WGM resonances and shape the transmission spectrum of sphere-coupled waveguides. Initial results from coupling two spheres to form a so-called "photonic molecule" [12] show the mode-splitting and enhanced wavelength selectivity expected from coupling two resonators.

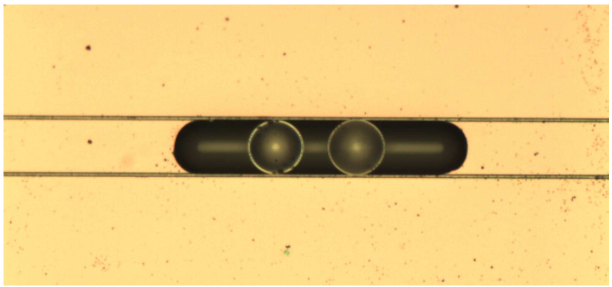

Figure 4. 60 micron microspheres assembled between waveguides

V. CONCLUSIONS

High-quality microspheres suitable for all-optical switching and lasing have been realised from advanced glasses and assembled on photolithographically structured substrates. Coupling to waveguides shows promise for the realisation of compact, highly functional photonic devices.

ACKNOWLEDGEMENT

The authors thank Prof Y. Ohishi of Toyota Technological Institute, Nagoya, Japan, for providing the tellurite glasses.

REFERENCES

[1] M.L.Gorodetsky A.A. Savchenkov and V.S. Ilchenko, "Ultimate Q of optical microsphere resonators", Opt. Lett., **21**, pp. 453-455 (1996).

[2] D.K. Armani, T.J. Kippenberg, S.M. Spillane and K.J. Vahala, "Ultra-high-Q toroid microcavity on a chip", Nature, **421**, pp. 925-929 (2003).

[3] Q. Xu, D. Fattal and R.G. Beausoleil, "Silicon microring resonators with 1.5-µm radius", Optics Express, **16**, pp. 4309-4315 (2008).

[4] K. Djordjiev, S.J. Choi, S.J. Choi and P.D. Dapkus "Microdisk tunable resonant filters and switches", IEEE Photon. Technol. Lett., **14**, pp. 828-830, (2002).

[5] T. Feuchter, E.K. Mwarania, J. Wang, L. Reekie and J.S. Wilkinson, "Erbium-doped ion-echanged waveguide lasers in BK-7 glass", IEEE Photon. Technol. Lett., **4**, pp. 542-544, (1992).

[6] J. Requejo-Isidro, A.K. Mairaj, V. Pruneri, D.W. Hewak, M.C. Netti and J.J. Baumberg, "Self-refractive nonlinearities in chalcogenide based glasses", J. Non-Crystalline Solids, **317**, pp. 241-246 (2003).

[7] G.S. Murugan, T. Suzuki and Y. Ohishi, "Raman characteristics and nonlinear optical properties of tellurite and phosphotellurite glasses containing heavy metal oxides with ultrabroad Raman bands", J. Appl. Phys., **100**, 023107 (2006).

[8] G.R. Elliott, D.W. Hewak, G.S. Murugan and J.S. Wilkinson "Chalcogenide glass miorospheres; their production, characterization and potential", Optics Express, 15, pp17542-17553 (2007).

[9] E.J. Tull, P.N. Bartlett and K.R. Ryan, "Controlled assembly of micrometer-sized spheres: Theory and application", Langmuir, **23**, pp. 7859-7873 (2007).

[10] E.J. Tull, P.N. Bartlett, G.S. Murugan and J.S. Wilkinson "Manipulating spheres that sink:assembly of micrometer sized glass spheres for optical coupling", Langmuir, **25**, pp. 1872-1880 (2009).

[11] Y. Panitchob et al., "Whispering gellery mode spectra of channel waveguide coupled microspheres", Opt. Express, **16**, pp. 11066 (2008).

[12] G.S. Murugan, J.S. Wilkinson and M.N. Zervas, "Waveguide coupling to size-mismatched bispheres", MOC 07, Japan (2007).