Hybrid multi-chip assembly of optical communication engines via 3-D nanolithography

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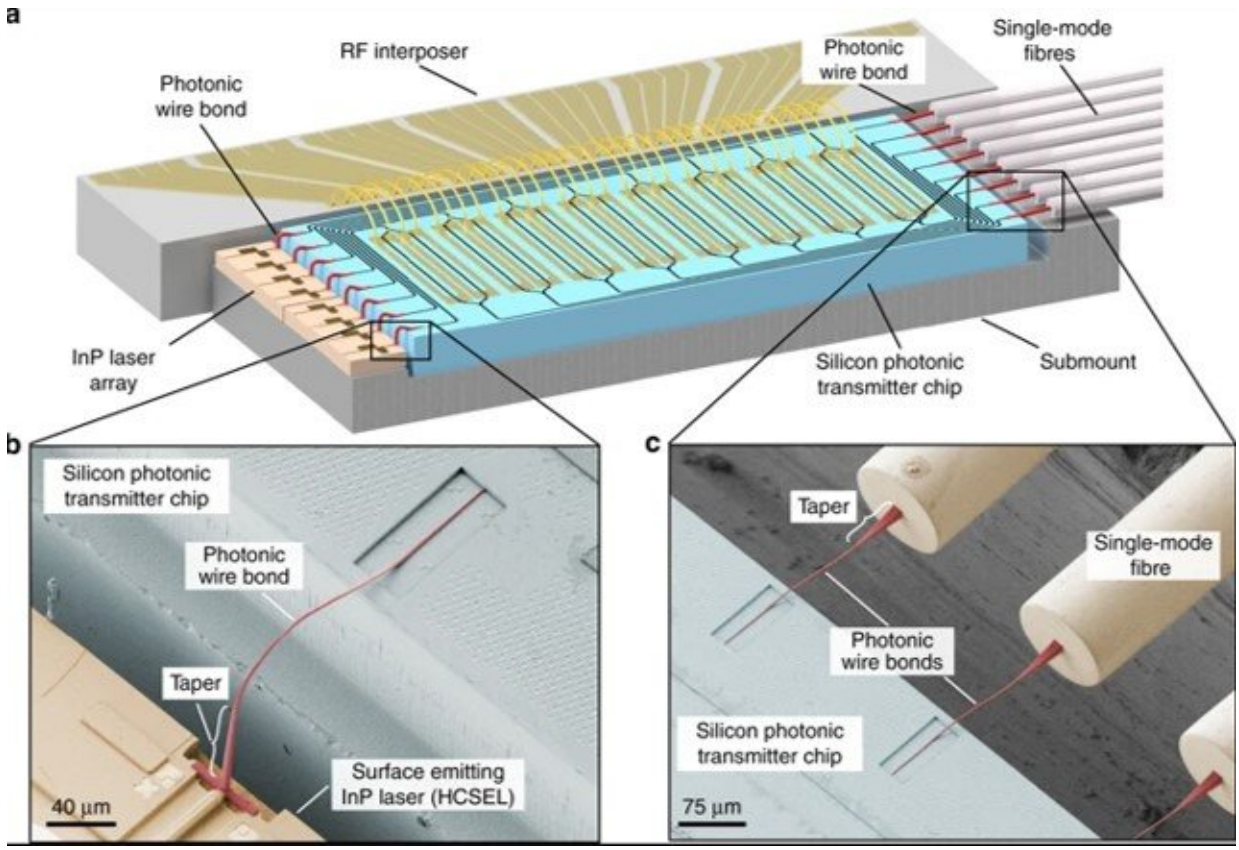
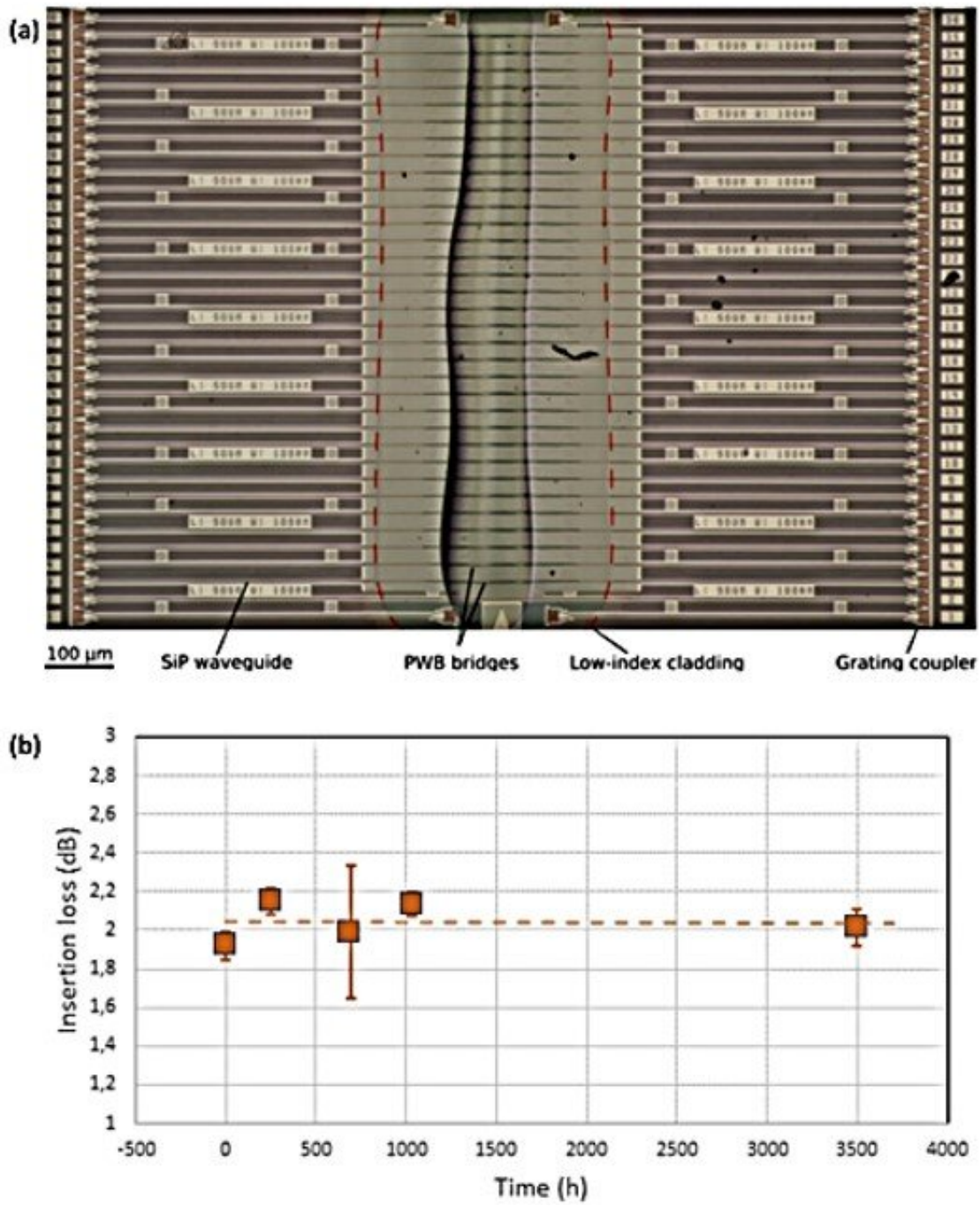


Concept and implementation of hybrid multi-chip modules (MCMs) by 3D nano-printing of photonic wire bonds (PWBs). (a) Illustration of an eight-channel transmitter, realized as a hybrid MCM comprising 3D-printed PWBs shown in red. PWBs allow efficiently connections between photonic integrated circuits (PICs) that are realized on different integration platforms, thereby combining the complementary strengths of the underlying material system. The illustrated

transmitter combines efficient InP lasers with electro-optic modulators on a silicon photonic chip. The modulator array is electrically driven via an RF fan-in and connected to an array of single-mode fibres. (b) Interface between an InP laser chip and the silicon photonic transmitter chip. The light source is realized as a horizontal cavity surface emitting laser (HCSEL), consisting of a waveguide-based optical cavity in the substrate plane and an etched 45° mirror that redirects the light towards the substrate-normal direction17. (c) Fibre-to-chip interface. For efficient coupling to the large mode-field of the SMF, the PWBs are designed to have a larger cross section towards the fibre facet. The 3D freeform trajectory of the PWBs is adapted to the exact position of the corresponding interfaces and thereby replaces high-precision active alignment of the chips. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-0272-5

Three-dimensional (3-D) nanoprinting of freeform optical waveguides also known as photonic wire bonding can efficiently couple between photonic chips to greatly simplify optical system assembly. The shape and trajectory of photonic wire bonds offers a key advantage as an alternative to conventional optical assembly techniques that rely on technically complex and expensive high-precision alignment. In a new study now published on *Nature: Light, Science & Applications*, Matthias Blaicher, Muhammed Rodlin Billah and a research team in photonics, quantum electronics and microstructure technology in Germany, demonstrated optical communication engines. The device relied on photonic wire bonding to connect arrays of silicon photonic modulators to lasers and single-mode fibers. They engineered the photonic wire bonds onto the chips in the lab using advanced 3-D lithography to efficiently connect a variety of photonic integration platforms. The scientists simplified the assembly of advanced photonic multistep modules to transform a variety of applications ranging from high-speed communications to ultra-fast signal processing, optical sensing, and quantum information processing.

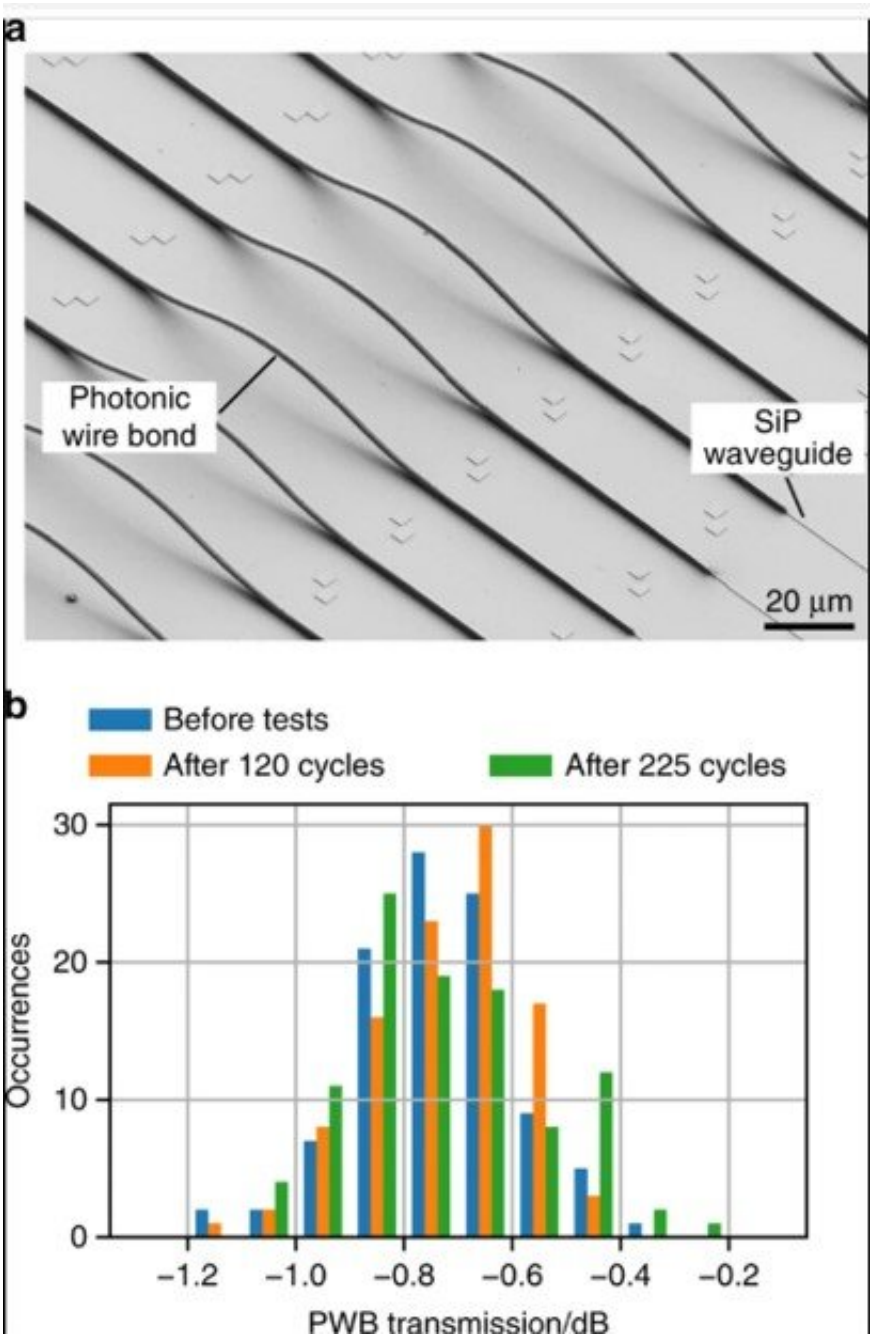
Photonic integration is a key method to transform a variety of quantum technologies. Most commercial products in the field rely on the discrete assembly of photonic chips that require coupling elements such as on-chip adaptors and bulky microlenses, or redirecting mirrors. Assembling such systems require technically complex active alignment, to continuously monitor the coupling efficiency during device development . Such techniques are classified as high cost and low throughput methods, and as a result they set back any advantages of wafer-scale mass production of photonic integrated circuits (PIC). In this study, Blaicher et al. combined the performance and flexibility of conventional systems with the compactness and scalability for monolithic integration using advanced additive nanofabrication techniques. To engineer freeform polymer waveguides on photonic devices, the team relied on direct-write-two-photon-lithography. The method is also known as photonic wire bonding to allow highly efficient optical coupling in a fully automated process.



Scalability and stability of photonic wire bonds. (a) Micrograph of a field of densely spaced on-chip PWB bridges connecting down-tapered ends of SiP strip waveguides. The PWB are covered with a protective low-index cladding. The sample has been subjected to temperature 500 cycles of -40°C/+85°C in addition to 500 hours of damp heat test at +85°C and 85% relative humidity. No change in transmission nor any physical changes such as delamination of the cladding

material from the SiP chip was observed. (b) Long-term damp-heat test of PWB at 85°C and 85 % relative humidity. In this sample, the average insertion loss amounts to approximately 2 dB - slightly higher than in the one shown in Fig. 2 of the main manuscript. This loss remains stable over the whole 3500 h of damp-heat tests. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-0272-5

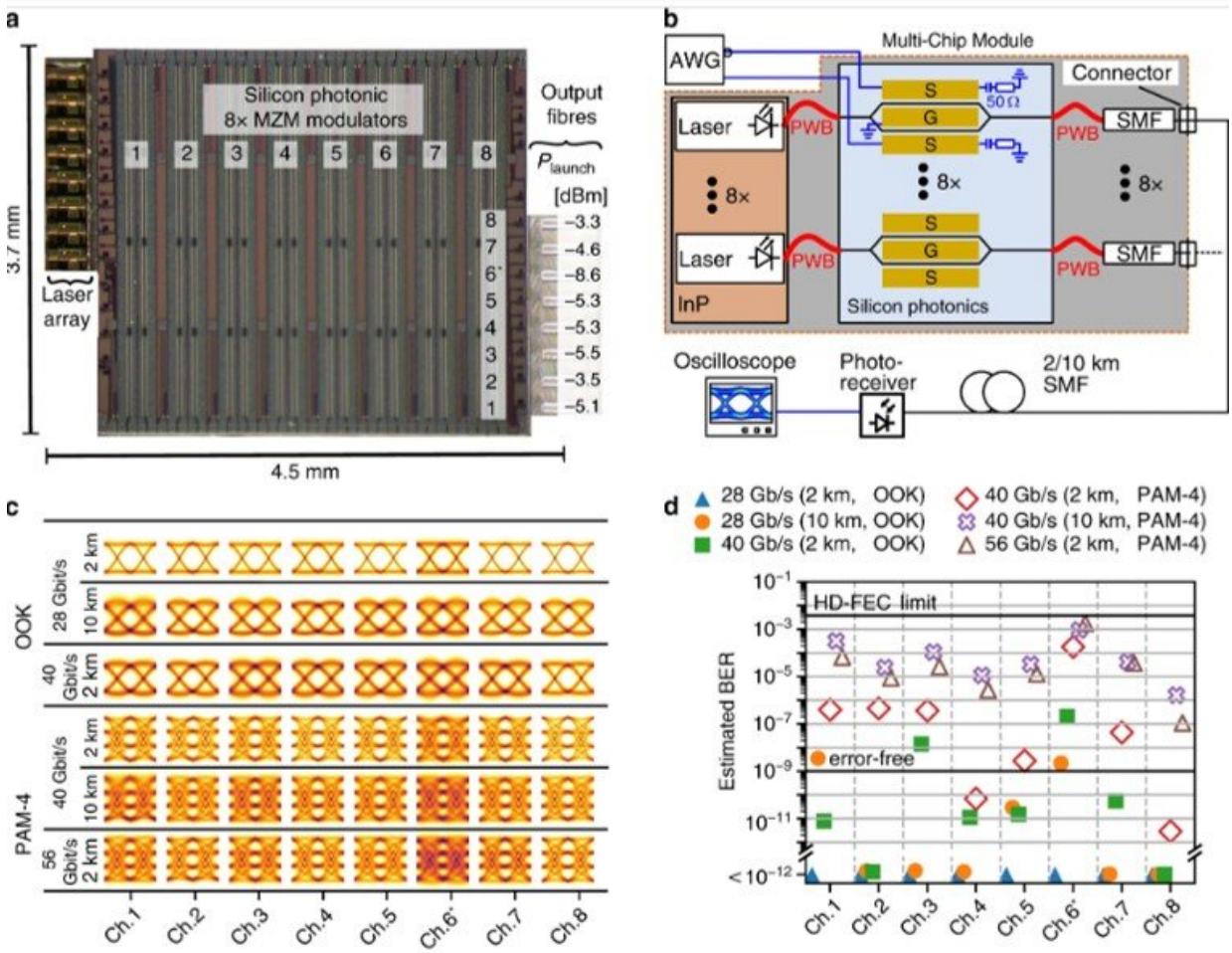
During the experiments Blaicher et al. engineered 100 densely spaced photonic wire bonds (PWBs). The experimental results formed the basis for the simplified assembly of advanced photonic multi-chip systems. The experimental module contained multiple photonic dies based on different material systems including indium phosphide (InP) or silicon-on-insulator (SOI). The experimental steps of assembly did not require high-precision alignment and the scientists achieved chip-to-chip and fibre-to-chip connections using 3-D freeform photonic wire bonds. Before fabricating PWBs, Blaicher et al. detected on-chip alignment markers using 3-D imaging and computer vision techniques. Thereafter, they used two-photon lithography to fabricate the PWBs, allowing resolution at the sub-micron scale. The team placed optical clips side by side in the setup to prevent thermal bottlenecks for efficient thermal connection. The hybrid multichip module (MCM) relied on efficient connections of the silicon photonic (SiP) chip to the InP light source and to the output transmission fiber. The team realized the light sources as horizontal cavity surface emitting lasers (HCSELs) and when they combined the PWBs with microlenses, they could facilitate optical out-of-plane connections to the chip surface.



Automated fabrication and environmental stability. (a) Array of densely spaced on-chip PWB test structures. The scanning electron microscope (SEM) image depicts a subset of an array of 100 PWBs realized on a dedicated a silicon photonic (SiP) test chip. The PWB bridges connect tapered ends of SiP strip waveguides, separated by 100 µm. High-resolution 3D imaging in combination with computer vision is used for automated detection of the optical coupling with high precision (better than 100 nm) and enables highly reproducible lithographic definition of the freeform structures. The waveguides are finally

embedded into a UV-curable low-index polymer (not shown), which acts as a protective cladding and allows adjustment of the refractive-index contrast. (b) Histogram showing measured insertion losses of 100 on-chip PWB bridges directly after fabrication (blue) as well as after temperature cycling tests, comprising 120 (orange) and 225 (green) cycles. The indicated transmission comprises the propagation loss in the freeform polymer waveguide of the PWBs as well as the overall loss of both double-taper interfaces to the adjacent SiP strip waveguides. After fabrication, the PWB bridges exhibits an average insertion loss of 0.73 dB and a standard deviation of 0.15 dB, and the loss of the worst structure was 1.2 dB. These figures are essentially unaffected by the temperature cycles. The slightly different shapes of the histograms are attributed to the fact that the samples had to be removed from the measurement setup for temperature cycling, leading to small changes in fibre-chip coupling efficiency. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-0272-5

In the first experiment, using test chips fabricated via deep-UV lithography, the team showed that PWBs provided low-loss optical connections. Each test chip contained 100 test structures to separate the PWB loss from fibre-chip coupling loss. The in-lab fabrication of PWB was fully automated, taking approximately 30 seconds per connection and the process could be further accelerated. The team obtained comparable results by replicating the experiments on other test chips to clearly demonstrate the excellent reproducibility of the process. The scientists then exposed the sample to multiple temperature cycles varying from -40°C to 85°C to prove reliability of the structures under technically relevant environmental conditions. The samples did not undergo performance degradation or deformation during the experiments. To understand high-power handling capability of the PWB structures, they subjected the samples to continuous laser irradiation at 1550 nm, with increasing optical power levels. The experiments showed the possibility of using PWBs for high performance in industrially relevant environments and under realistic power levels.

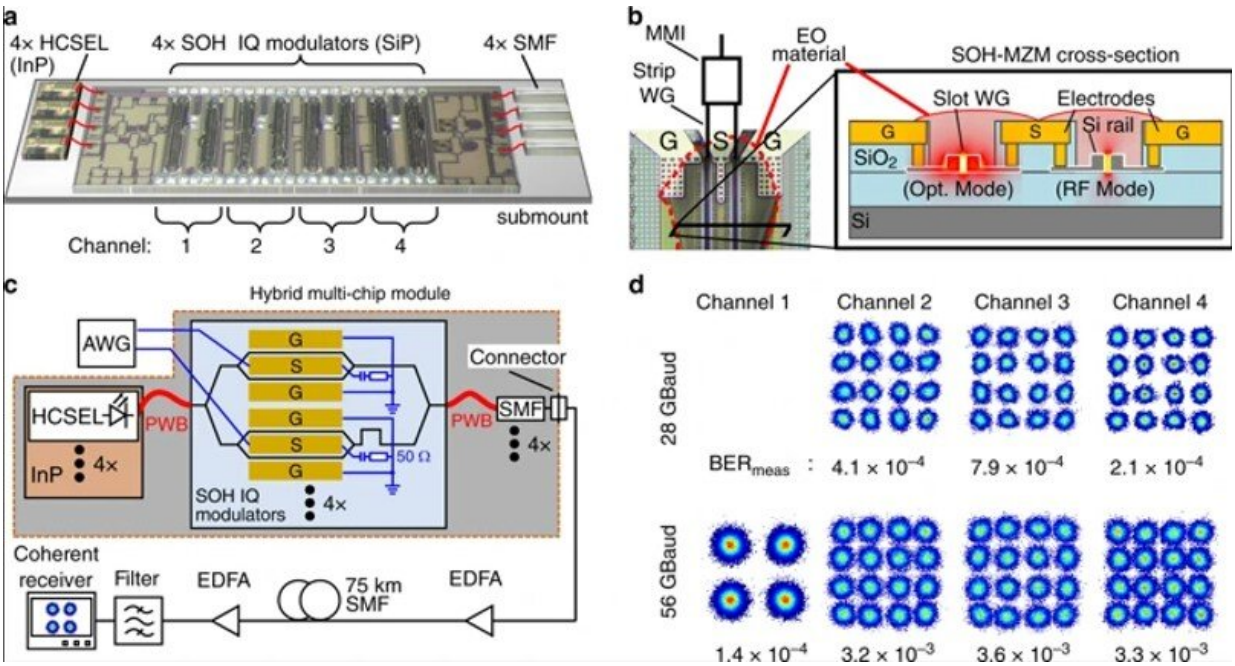


Eight-channel multi-chip transmitter (Tx) module combining InP laser arrays and SiP modulator arrays. The module is geared towards transmission in data-centre and campus-area networks with maximum distances of 10 km, using simple intensity modulation and direct detection techniques. (a) Light-microscope image of the Tx assembly realized according to the experimental concept. The array of Mach-Zehnder modulators (MZMs) is connected to an array InP-based HCSEL ("Laser array") and to an array of single-mode fibres by PWBs (not visible here). The launch powers, measured in the single-mode fibre for maximum transmission of the modulators, are sufficient for transmission over distances typical for data centre and campus-area networks, without the need of optical amplifiers. Launch power variations are mainly attributed to non-ideal coupling to and from the SiP chip. Channel 6* contains an additional on-chip 3 dB splitter for testing, which leads to additional loss. (b) Experimental setup for

transmission demonstrations using different modulation formats and distances. An arbitrary-waveform generator (AWG) is used to drive the MZMs. In the demonstration, the modulators are operated sequentially via an RF probe delivering the drive signal at the input and another RF probe to provide a 50 Ω termination at the output. The optical signal is sent through up to 10 km of standard SMF and is detected with a photoreceiver that contains a photodetector along with a high-speed transimpedance amplifier. A real-time oscilloscope is used to capture the electric signals for subsequent offline processing. (c) Eye diagrams for transmission over various distances, with different modulation formats and symbol rates. As expected from the launch powers, Channel 8 shows the widest-open eyes, whereas Channel 6 is distorted by noise. d Estimated bit error ratios (BERs) for transmission over various distances, with different modulation formats and symbol rates. For all experiments, the BER stays below the 7% HD-FEC threshold. The aggregate module line rate amounts to a 448 Gbit/s. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-0272-5

To then demonstrate the technical feasibility of the PWB approach, Blaicher et al. realized a functional eight-channel photonic multi-chip transmitter (Tx) engine that combined InP-based laser arrays and SiP (silicon photonic chip) modulator arrays to modulate intensity. The complete assembly contained two arrays of four horizontal cavity surface emitting lasers, connected via PWBs to an array of travelling-wave-depletion-type Mach Zehnder modulations. The demonstration was a proof-of-principle, leaving room for optimization.

During the second series of experiments, the team formed a four-channel multi-step transmitter module for coherent communication. In this module, they combined hybrid multi-chip integration containing PWBs with hybrid on-chip integration of electro-optic modulators, to combine the SiP nanowire waveguides with highly efficient electro-optic materials. The setup resulted in highly efficient devices with low power consumption.



Four-channel coherent transmitter module combining hybrid integration concepts on the chip and package levels. (a) Artist's impression of the multi-chip-module (MCM) consisting of four InP-based HCSEL light sources, an array of four silicon-organic hybrid (SOH) modulators, and four transmission fibres, all connected by photonic wire bonds (PWBs). The overall footprint of the complete Tx module amounts to 4 × 1.5 mm2. (b) Top view and cross section of an SOH Mach-Zehnder modulator (MZM). The organic electro-optic (EO) material (red contour) is micro-dispensed after fabrication of the PWB. The MZM consists of two slot-waveguide (WG) phase modulators, driven in push-pull mode by a single coplanar transmission line in ground-signal-ground (GSG) configuration. Within the slot-waveguide phase shifters, the dominant electrical component of the optical quasi-TE mode exhibits a strong overlap with the electrical RF-mode field, resulting in a high modulation efficiency32. (c) Experimental setup. Each HCSEL feeds an IQ modulator. Electric drive signals for the modulators are provided by an arbitrary-waveform generator (AWG). The optical signal is then amplified, sent through 75 km of standard SMF, and detected by a coherent receiver. A real-time oscilloscope captures the signal for subsequent offline processing. (d) Constellation diagrams and associated measured bit error ratios (BERs) for signalling with 16QAM at symbol rates of

28 GBd and 56 GBd. The performance of Channel 1 was impaired by lower launch power such that only QPSK transmission could be used. All BER values stay below the threshold for hard-decision forward-error correction FEC with 7% coding overhead. The aggregate module line rate amounts to 784 Gbit/s. Credit: Light: Science & Applications, doi: 10.1038/s41377-020-0272-5

In this way, Matthias Blaicher, Muhammed Rodlin Billah and colleagues conducted 3-D nanofabrication of photonic wire bonds (PWBs) to overcome the existing limits of hybrid photonic integration approaches. The team demonstrated the viability of the experimental setup using two key protocols to realize two different hybrid multi-chip transmitter engines. While the team focused on transmitter modules for high speed optical communication during this work, the technology may unlock a wide range of novel applications that benefit from the advantages of hybrid photonic integration.

More information: 1. Hybrid multi-chip assembly of optical communication engines by in situ 3D nano-lithography www.nature.com/articles/s41377-020-0272-5 Matthias Blaicher and Muhammad Rodlin Billah et al. 27 April 2020, *Light: Science & Applications*.
2. Advances in terahertz communications accelerated by photonics www.nature.com/articles/nphoton.2016.65 Tadao Nagatsuma et al. 31 May 2016, *Nature Photonics*
3. Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip. www.nature.com/articles/s41586-018-0028-z Amir H. Atabaki et al. 18 April 2018, *Nature*.