Signal processing of optical signals is applied today in many fields including telecommunications, metrology, and in various disciplines in optical sensing/analysis (ranging from environmental sensing through the biological and medical sciences to security). In order for optical signal generation to be used in the future it is essential to be able to generate optical signals with parameters that go well beyond those attainable electronically – indeed we contend that optical signals will need to promise at least an order of magnitude better performance than those obtained electronically. Thus, arbitrary signals with bandwidth and/or repetition rate of ~1 THz (electronics signals are typically bandwidth/repetition rate limited to ~100 GHz) will be required. To achieve this goal, full control over the amplitude and phase of large-bandwidth high repetition rate optical signals is needed.

Within this project, we investigated one of the possible paths to achieve these goals. It is based on the coherent synthesis of arbitrary shape high-repetition rate optical signals through coherent superposition of multiple phase locked high-quality local oscillators (lasers) operating at spectrally-distant optical frequencies (e.g., on a 1 THz grid). To achieve the desired high level of coherence among these local oscillators spaced on a frequency grid that cannot be spanned by standard electronics means, we phase locked them to a high-quality optical 'ruler', more specifically an optical comb. This promises to bring several important advantages over the direct use of an optical comb, which is the technique predominantly used today. These are mainly: (i) a large spacing of the frequency lines used for the synthesis (e.g., 1 THz, as opposed to 250 MHz – 10 GHz for current combs) leading to ultra-high repetition rates (e.g., 1 THz), (ii) a high power-per line (e.g., 50 mW, as opposed to ~1 µW for comb and allowing very high Optical Signal to Noise Ratios), and (iii) full arbitrary waveform shaping capabilities in the spectral domain due to the lower spectral resolution required (e.g., 1 THz, as opposed to 250 MHz-10 GHz for comb). We believe that this new idea will provide a major breakthrough in the performance of optical synthesizers and thus also significantly broaden the application potential for such systems. For example, the availability of a high power, phase locked source would be particularly useful in the pumping of phase sensitive parametric amplifiers and phase based regenerators – an area of significant current interest and for which low noise is of paramount importance if their full potential is ever to be realized.

The vision behind the proposed work is sketched in Fig. 1, in which we have considered as means of a specific example the generation of a 100-GHz repetition rate train of square-like pulses. First, multiple slave lasers are spaced to sit on a precise grid (ten lasers on a 100 GHz grid for the example shown). These slave lasers are then phase locked to an optical comb which is generated from a single master laser (a high performance continuous wave master oscillator in this particular example). Subsequently, the individual outputs from the slave lasers are coherently combined in a multiplexer that can also provide arbitrary amplitude and phase control for each slave beam. Owing to the high frequency spacing targeted the coherent beam combination should be possible using standard dense wavelength division multiplexing (DWDM) technology. It is worth noting that in the future, we believe that most of the components could be integrated onto a single photonic chip, as suggested in Fig. 1.

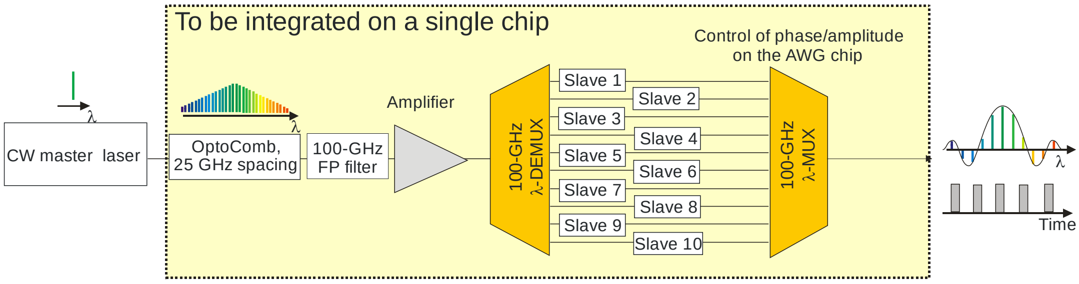

Fig. 1: A schematic of the ultrafast pulse synthesizer. In this example, it is used for generation of square-like, 100-GHz repetition rate chirp-free pulses.

The key phenomenon in our approach is phase locking of a semiconductor laser to a single comb tooth of a frequency comb. We chose optical injection locking assisted by an electronic phase locked loop to achieve high-performance phase locking over long period of time (e.g., 24 hours). After setting up this phase locker using a single laser (locked to one comb tooth), we developed (in collaboration with National Physics Laboratory in London) a range of highly-sensitive and complex characterization techniques for precise characterization of the phase locking process (via measurement of phase noise) over short (>100 Hz) as well as long (>8 hours) time scales. Using these newly-built characterization set-ups, we were able to tune the parameters of the developed phase locker (e.g., injection optical power, feedback loop parameters) to obtain optimum performance. We achieved power amplification of more than six orders of magnitude of the selected comb tooth and Allan deviation of 4×10^{-19} (at 1000 s average time). Following this step, the phase locker was replicated and two lasers were locked to two selected comb teeth. This allowed us to perform detailed phase noise characterization over large bandwidths and to use alternative characterization techniques to confirm the validity of our result. Finally, the phase locker was further replicated and five phase lockers and lasers were integrated into three 19’’ racks. The device is now being tested in various applications and forms part of an on-going PhD thesis project.