Photonic Techniques for Microwave Frequency Synthesis

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I INTRODUCTION
Optical synthesis of microwave signals is attractive for three main reasons. First, it offers the possibility of compact and efficient sources at frequencies where conventional electrical sources are bulky and very inefficient, such as in the THz region. Second, it enables rapid frequency stepping across many octave bandwidths within the microwave spectrum, which is difficult to achieve with electrical sources. Finally, it enables frequency generation to be removed through optical fibre to a convenient location, with little performance penalty. The object of this paper is to review techniques for the optical synthesis of microwave signals and suggest some possibilities for the creation of new sub-systems of enhanced capability.

II SOURCE OPTIONS
For microwave frequency intensity modulation the only suitable directly modulated source is the semiconductor laser, and bandwidths in excess of 30GHz have been demonstrated [1]. External modulators can offer reduced dispersion penalties in fibre transmission through low chirp operation. Mach-Zehnder interferometric modulators have been realised in both lithium niobate [2] and III-V semiconductor technologies [3] with -3 dB bandwidths exceeding 50 GHz. Semiconductor electro-absorption modulators have also achieved impressive results, with bandwidths exceeding 40 GHz [4]. To access frequencies beyond these limits different techniques are required. These may be conveniently categorised into single optical source and multiple source techniques. In the single source techniques the output from the source is fed to a fast photo-detector, possibly following some optical filtering operations. In the multiple source technique, the outputs from two or more sources are combined optically before photo-detection.

SINGLE SOURCE TECHNIQUES
The most commonly used single source for optical synthesis of microwave signals is the actively mode-locked laser [5]. This produces a comb spectrum in the frequency domain with line separation set by the drive frequency and -3dB frequency related to the pulse width by \( f_c = 0.4/f_p \). where \( f_p \) is the pulse width. Since pulse widths of less than 1 ps are readily obtainable [6], frequencies greater than 400 GHz can be produced.

The comb line spacing in a mode-locked laser is determined by the laser cavity length and is therefore not readily tuneable. Figure 1 shows an alternative comb generator system capable of generating lines with frequencies exactly determined by single optical and microwave reference inputs. Comb generation is achieved by successive phase modulation of the laser reference line in an amplified re-circulating loop. In an experimental demonstration of this system, with a reference laser wavelength of 1,529 nm and comb line spacing set to 18 GHz, over one hundred comb-lines were observed within a 40 dB power envelope, corresponding to a comb spectrum width of 1.8 THz [7]. Individual comb lines can be selected using injection locked DFB lasers and heterodyned to generate microwave and millimetre-wave signals with SSB noise of -74 dBc/Hz at 100 kHz offset, limited by decorrelated noise between the two injection locking paths [8].

Fig. 1: Amplified fibre loop optical comb generator.

The output power of a mode-locked laser is distributed between all the lasing modes, so that if only a single output frequency is to be synthesised the conversion efficiency is low. This limitation can be overcome by restricting the gain bandwidth of the laser to permit only the wanted modes to lase, giving a gain-bandwidth reduced actively mode-locked (GRAM) laser. Using this approach conversion of over 45% of the total laser output power to
microwave power at the required frequency has been shown to be possible [9].

MULTIPLE SOURCE TECHNIQUES
Photodetection of the combined outputs of two tuneable lasers can be used to generate frequencies limited only by the photodetector bandwidth. Semiconductor lasers are preferred as sources due to their compactness, efficiency and low cost, but their wide linewidths (1MHz to 50 MHz for typical DFB devices) require the use of an optical locking technique to achieve acceptable levels of phase noise in the generated signal. Injection locking (IL) to harmonics of a modulated master laser can give low phase noise [10] but mK tolerance temperature stabilisation of the slave lasers is required to keep them within the stable locking range. Optical phase lock loop (OPLL) techniques require loops having extremely wide bandwidths and short loop propagation delays [11]. Figure 2 shows an architecture which overcomes these limitations, the heterodyne optical injection phase lock loop (OIPLL) [12].

![Fig. 2. Experimental all-fibre OIPLL system. ML: master laser, SL: slave laser, PD: photodetector, LF: loop filter, AD: adjustable delay line.](image)

In this approach a narrow band phase lock loop is used to maintain the slave laser at the optimum frequency for injection locking and provide close-to-carrier phase noise reduction, with injection locking being used to obtain broadband phase noise reduction. Figure 3 compares the phase noise in the generated signal with that of the multiplied reference for an output frequency of 36 GHz. The phase noise is better than -92 dBc/Hz at 10kHz offset from the carrier and the noise penalty relative to the multiplied reference is less than 4 dB, except at large offsets, where residual phase noise of the wide (220 MHz heterodyne) linewidth lasers used dominates.

**III CONCLUSION**
The techniques described can be used to generate signals at frequencies limited only by available

![Fig. 3 Plot of SSB phase noise spectral density (dBc/Hz) against offset from 36 GHz carrier (Hz). Upper trace: detected OIPLL output; lower trace: multiplied reference phase noise.](image)

photodetectors, with spectral purity competitive with conventional sources in the microwave region and superior in the upper mm-wave region. Recent developments in mm-wave bandwidth high power photodetectors [13] are likely to lead to increased interest in photonic signal generation for upper mm-wave and THz systems, with emphasis on broadband communications and imaging applications.

**REFERENCES**