OPTICAL SYNTHESIS OF MICROWAVE SIGNALS

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ABSTRACT

Microwave signals can be generated by the photo-detection of multiple optical signals. This approach has potential for the generation of signals having characteristics not readily obtainable by other means, such as fast tuning over multi-octave ranges, low dispersion and non-linearity penalties in millimetre-wave over fibre transmission and compact millimetre-wave local oscillator generation. Obtaining the spectral purity required for practical applications is however a significant challenge. This paper describes techniques for the optical synthesis of microwave signals, focusing on optical heterodyne generation techniques and including recent results for a high spectral purity optical injection phase lock loop.

I. INTRODUCTION

Quantum efficient depletion layer photodetectors having 3dB bandwidths in excess of 100GHz were first reported several years ago [1]. For operation well within the 3dB bandwidth a simple current generator model for the photodiode can be used. Consider two monochromatic optical signals having polarisation matched electric fields

\[ E_1 = \hat{E}_1 \cos(\omega_1 t + \phi_1) \]  

and

\[ E_2 = \hat{E}_2 \cos(\omega_2 t + \phi_2) \]

where \( \omega \) is the signal frequency and \( \phi \) the signal phase. For \( \omega_1 = \omega_2 \) and perfect wavefront overlap the photodiode output current is given by

\[ i \propto \hat{E}_1 + \hat{E}_2 + 2 \hat{E}_1 \hat{E}_2 \cos(\omega_1 - \omega_2 + \phi_1 - \phi_2) \]

Using the relationship

\[ \hat{E}^2 = 2 \frac{Z_o P}{A} \]

where \( A \) is the photodiode area, \( P \) the optical power and \( Z_o \) the characteristic impedance of the medium where the power is measured, the photodiode current can be written as
\[ i = R [ P_1 + P_2 + 2 \sqrt{P_1 P_2} \cos(\omega_1 - \omega_2 + \phi_1 - \phi_2)] \]

where R is the photodiode responsivity. Note that a signal is generated at the difference frequency between the two optical signals and that the microwave power generated is proportional to the product of the powers of the incident optical signals. The analysis extends naturally to multiple frequency optical inputs. Note also that the spectral purity of the generated signal depends on the correlation of noise between the two inputs.

In this paper correlation of the noise by optical phase lock loop will be considered followed by a description of a locking technique that greatly eases the realisability of systems using semiconductor lasers; the optical injection phase lock loop (OPLL). A conclusion section discusses applications of the techniques described and suggests avenues for further work.

2. OPTICAL PHASE LOCK LOOP
The simplest heterodyne microwave generation scheme would comprise two polarisation matched lasers with overlapped wavefronts incident on a suitable photodiode. Laser diode pumped Nd:YAG lasers have been used in this way and can offer a beat linewidth in the kHz region [2]. Tuning is by crystal heating and PZT applied stress giving maximum rates of order 1 GHz/µs. Semiconductor lasers can offer much higher tuning rates, > 100 GHz/µs, and are less bulky and expensive, but have much wider linewidths, typically in the 3 MHz - 50 MHz range. The emission frequency is also a strong function of temperature and current, values of 30 GHz/K and 3 GHz/mA being typical of distributed feedback (DFB) lasers operating at a wavelength of 1,550 nm. Whilst semiconductor lasers can be stabilised by locking their frequency to a cavity resonator, such as a Fabry-Perot etalon, the system is complex and wideband suppression of phase noise is not possible [3]. Figure 1 shows an alternative technique, the optical phase lock loop (OPLL). Samples of the outputs from the two lasers are combined, photo-detected and the resulting heterodyne signal compared with a microwave reference to derive an error signal which controls the frequency of one laser to lock the heterodyne frequency to the supplied reference.

The main difficulty in implementing OPLLs arises from the wide linewidth typical of semiconductor lasers which requires a very wide bandwidth, short propagation delay control loop. Figure 2 shows the dependence of the mean time to cycle slip on loop propagation delay for lasers of combined linewidth 8 MHz [4]. It is clear that to obtain reliable operation delays of less than 0.35 ns are required, corresponding to a free space path length of less than 105 mm. Considering that this includes delay in both optical and electronic components of the system the difficulties in OPLL construction become clear.

Optical injection locking (OIL), in which light from a modulated master laser is injected into a slave laser to lock its output frequency [5], does not present the loop delay restriction and the level of phase noise can be controlled by the amount of light injected into the slave laser cavity. However, the OIL locking range can be severely reduced due to instabilities occurring in the locking process above critical levels of injection [6].
3. OPTICAL INJECTION PHASE LOCK LOOP
We have developed a new loop architecture, combining OPLL and OIL techniques, the optical injection phase-lock loop (OIPPL) [7]. This system allows low phase error variance to be achieved for loops using wide linewidth lasers and having significant loop propagation delay, offering improved performance over either OPLL or OIL systems used individually. An experimental homodyne OIPPL using lasers of summed linewidth 36 MHz achieved a phase error variance of less
than 0.006 rad$^2$ in measurement bandwidth 500 MHz and had a stable tuning range exceeding 26 GHz, limited only by saturation of the loop filter electronics [8].

Figure 3 shows an experimental heterodyne OIPLL. Part of the light emitted by the master laser is injected into the slave laser cavity. The other part is combined with the slave laser output light and photodetected. The resulting electrical signal is compared with the microwave reference signal in the phase detector. The loop filter includes an integration stage to give a second order type II loop response.

![Diagram](image)

Figure 3 - Heterodyne OIPLL experimental set-up. ML: master laser; SL: slave laser; I: isolator; H: half-wave plate; Q: quarter-wave plate; PBS: polarising beam splitter; NBS: non-polarising beam splitter; M: mirror, LSA: lightwave signal analyser, FPI, Fabry-Perot interferometer.

The reference signal is also used to modulate the master laser so as to produce FM sidebands at harmonics of the reference frequency. The slave laser can be locked to the chosen harmonic by adjusting its bias current. Since phase comparison takes place at both the slave laser and the phase detector an adjustable mirror is used to match the path lengths and so avoid competition between the two locking processes.

Figure 4 shows the detected modulated output for a reference frequency of 8 GHz and lasers of summed linewidth 36 MHz. The noise power spectral density is -94 dBc/Hz at 10 kHz offset, within 1 dB of the phase noise level of the microwave synthesiser used as a reference and the phase error variance is 0.003 rad$^2$ in a bandwidth of 100 MHz (limited by lightwave signal analyser noise floor). The hold-in range was greater than 24 GHz.

Harmonic locking was also shown to be possible with the OIPLL system. Since modulation of the master laser results in both intensity modulation (IM) and frequency modulation (FM), multiple side frequencies are generated. The hold-in range was 4 GHz. The hold-in range is lower than for fundamental locking because the injection ratio for the 16 GHz sideband is smaller at -37 dB resulting in reduced loop gain.

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Figure 4: Heterodyne OPLL spectrum. Injection ratio: -30 dB. Span = 200 MHz, resolution bandwidth = 3 kHz.

In contrast an OIL system using the same conditions had a stable tuning range of less than 2 GHz and it was not possible to achieve OPLL operation with the parameters used here.

4. CONCLUSIONS
The OPLL and related heterodyne techniques offer several attractions in microwave over fibre transmission systems. First, it is possible to apply baseband modulation to one of the laser outputs only and then combine master and slave laser outputs for transmission through fibre. This enables a modulator of modest bandwidth to be used, with the up-conversion to the required microwave frequency taking place at the receiver photo-detector. Further, since modulation is applied to one laser output only, dispersion effects are reduced, since they affect only the baseband signal for narrow linewidth sources. Second, where the heterodyne frequency and laser linewidths are substantially greater than the Brillouin linewidth [9] (20 MHz at a wavelength of 1.55 μm) the power that can be launched into an optical fibre link can be raised above the Brillouin limit for a conventionally modulated system, thus allowing an improvement in received signal to noise ratio. Third, the chirp characteristic of directly modulated sources can be avoided using the heterodyne technique, thus increasing the dispersion limited transmission distance. In practice the main limitation comes from the dispersion induced decorrelation of the phase noise on the two laser outputs and polarisation mode dispersion [10].

More generally, approaches based on laser heterodyning can be used for signal generation at frequencies limited only by the bandwidth of the photodetector used. They are thus attractive for local oscillator generation at the higher millimetre-wave frequencies where compact and efficient
conventional electronic sources are difficult to realise. The development of kHz linewidth semiconductor lasers [11] also makes practical optical heterodyne swept frequency sources of tuning speed and range much greater than YIG tuned oscillators. A further development that could offer wide bandwidth, uniform tuning response is the use of the quantum confined Stark effect for semiconductor laser tuning [12].

The main disadvantage of the heterodyne approach using semiconductor lasers is its complexity and the need for milli-Kelvin precision temperature control of the source lasers due to their high temperature tuning sensitivity. Work by Braun et al [13] on the integration of two DBR lasers has produced a source having a free running heterodyne temperature stability of better than 10 MHz/K, offering the possibility of widespread application of the techniques described above to microwave and millimetre-wave systems.

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