Phaselocked tunable subcarrier comb generator

S.-L. Tsao, J. Wu, T.-M. Chen and J.S. Wu

Indexing terms: Optical communication, Phaselocked loops, Phase modulation

A novel tunable subcarrier comb generator has been realised by dual-in-line phase modulators with optimum phase modulation indices. An optical heterodyne and microwave homodyne phaselocked loop is used to lock all optical carriers simultaneously. The hold-in range and linewidth are ~20MHz and 20Hz, respectively.

Introduction: Subcarrier multiplexing (SCM) and frequency division multiplexing (FDM) schemes present an attractive approach to the design of broad-band optical communication systems [1, 2]. Subcarrier or optical comb generators (OCGs) have the potential to provide extremely dense channels in SCM and FDM optical communication systems, and the application of phase array microwave antenna systems [3]. Obviously, flattened, dense and phase stabilised subcarriers or optical channel carriers are essential for realising these schemes. Various methods to achieve comb generator have been proposed [5].

In this Letter, we demonstrate a method to achieve phaselocked tunable subcarrier comb generators (TSCGs) with two cascade phase modulators by optical phaselocked loop (OPLL) technology. The OPLL technology also provides a convenient method for microwave homodyne and optical heterodyne phaselocking of optical carriers, and can be used to synchronise the laser frequencies in multioptical carrier communication systems. To determine the optimum phase modulation indices to achieve a maximally flattened optical comb spectrum, the theoretically relative power standard deviations of the optical carriers of the OCG are calculated. The experimental performance of the OPLL is also reported.

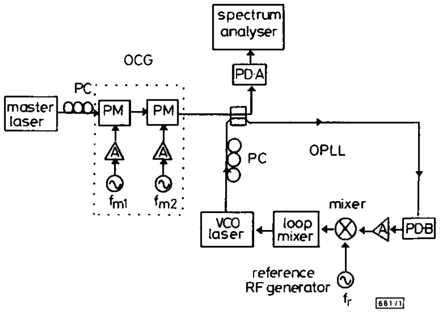

Fig. 1 *Schematic diagram of experimental setup of phaselocked TSCG*

PM: phase modulator, PD: *pin* photodetector, PC: polarisation controller, OPLL: optical phaselocked loop, OCG: optical comb generator

Principle of TSCG: The block diagram of the experimental setup of the phaselocked TSCG is shown in Fig. 1. Two tunable diode-pumped Nd:YAG lasers operating around 1.3µm are used as the master and VCO lasers. The light from the master laser is launched into the dual-in-line phase modulators, which are driven by two high power microwave tones f_1 and f_2. Thus, with large phase modulation indices β_1 and β_2, we can obtain a large number of optical carriers from the OCG. At the output of the OCG, the optical field of the comb carriers can be written as

$$E_{comb} = \sqrt{P_m}\cos[2\pi f_m t + \beta_1 \sin(2\pi f_1 t) + \beta_2 \sin(2\pi f_2 t)] \tag{1}$$

where P_m and f_m are the power and frequency of the master laser. To obtain equal channel spacing, f_2 should be a harmonic frequency of f_1. Therefore, it is possible to change the channel spacing by choosing the correct f_1, f_2, β_1 and β_2 to obtain a relatively flat optical comb spectrum. The optical carriers from the OCG are mixed with the VCO laser output by a 2 × 2 optical coupler, while the optical field of the VCO laser can be represented as

$$E_{VCO} = \sqrt{P_v}\cos(2\pi f_v t) \tag{2}$$

where P_v and f_v are the power and frequency of the VCO laser.

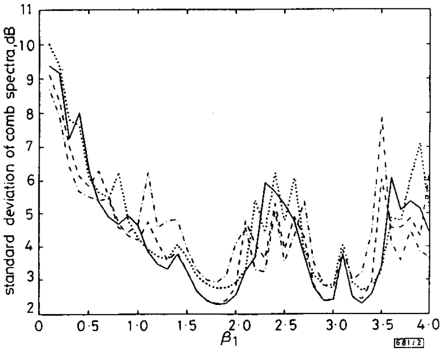

Fig. 2 *Standard optical power deviation of comb carriers for different* β_2 *against* β_1

·········· $\beta_2 = 2.7$
——— $\beta_2 = 2.9$
– – – – $\beta_2 = 3.1$
– · – · – $\beta_2 = 3.3$

The heterodyned comb spectra detected by the photodiode PD A are monitored by a microwave spectrum analyser. The output AC of the photodiode can be expressed as

$$i^{AC}(t) \propto R\sqrt{P_m P_v} \times \sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty} J_n(\beta_1) J_k(\beta_2)\cos 2\pi(f_{IF} + nf_1 + kf_2)t \tag{3}$$

where R denotes the responsivity of the photodiode, $J_n(\beta_1)$ and $J_k(\beta_2)$ represent the nth and kth order Bessel functions of the first kind and $f_{IF}(= |f_m - f_v|)$ is the intermediate frequency. To implement the phaselocked TSCG, we use an OPLL to lock the phase of the selected carrier as shown in Fig. 1. The VCO laser of the OPLL tracks the phase and the frequency of the selected carrier using a phase stabilising feedback loop. In this heterodyne OPLL, the OCG and VCO lasers oscillate at different frequencies to produce a set of microwave carriers after photodiode PD B. A mixer functioning as an RF phase detector compares the phases of the selected carrier and the reference signal f_r and generates the phase error signal which is further processed by an RC filter (τ = 5ms) and then applied to the PZT of the VCO laser to form the OPLL. Using 24 carriers to perform numerical optimisation, we obtain the standard deviation of carrier power of the OCG for various β_2 as a function of β_1, shown in Fig. 2. From the numerical results shown in Fig. 2, we find that some local optimum values as $\beta_1 = 1.8$, $\beta_2 = 2.9$; $\beta_1 = 3.3$, $\beta_2 = 2.9$; $\beta_1 = 2.9$, $\beta_2 = 2.9$; $\beta_1 = 3.0$, $\beta_2 = 3.1$ etc. can provide relatively flat comb spectra.

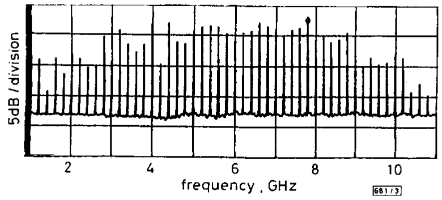

Fig. 3 *Comb spectrum measured at* $f_1 = 200$*MHz*, $f_2 = 1.2$*GHz*, $f_{IF} = 6$*GHz*, $f_r = 2$*GHz*, $\beta_1 = \beta_2 = 2.9$

Marker: 7.8GHz, –22.35dBm

Experimental results: We choose the same phase modulation index $\beta \simeq 2.9$ for the two phase modulators. The RF modulation frequencies for the dual-in-line phase modulators are set at f_1 = 200MHz and f_2 = 1.2GHz, respectively. Fig. 3 shows the measured phaselocked optical comb carriers with reference RF frequency f_r = 2GHz. We can choose the centre region of 24 carriers which gives the maximum power deviation below 5dB as subcarriers for applications. An expanded view of the optical comb spectra of Fig. 3 shows the linewidth of a selected optical carrier in Fig. 4. With a minimum resolution bandwidth of 10Hz (which is limited by the RF spectrum analyser), we can see that the 3dB linewidth of each carrier is below 20Hz.

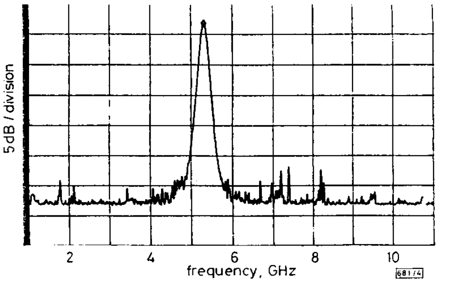

Fig. 4 *Spectrum of one carrier of comb carriers under phaselocked condition*

Vertical: 5dB/division, horizontal: centre: 1.999 998 800GHz, Span: 1kHz
Marker: 1.999 998 731GHz, -23.18dBm

The VCO laser is operating at 1319 nm with 1mW optical output power. A PZT element mounted on the Nd:YAG crystal provides fast frequency tuning. The frequency, tuning coefficient of the PZT is 5.5MHz/V. We find that this OPLL can provide a hold-in range of 20MHz. When the desired lockiug RF frequency falls into the range of 400kHz away from reference frequency f_r, the pull-in process of the OPLL drives the VCO laser slowly until the beat frequency approaches the reference frequency. Therefore, the pull-in range is 400kHz in our experiment. Furthermore, the lock-in range we measured is ~48kHz over which the OPLL acquires phaselocking without cycle slips.

Conclusions: We have implemented a tunable phaselocked optical comb generator by mixing two laser lights with one light being appropriately phase modulated. With the optimal modulation indices $\beta_1 = \beta_2$ 2.9 of the phase modulators, a phaselocked 24 carrier comb generator with maximum power deviation of 5dB is achieved. The OPLL tracking technique with a hold-in range of 20MHz is employed to achieve phaselocking for all the carriers generated by the OCG simultaneously. The 3dB linewidth of each optical carrier is less than 20Hz. The pull-in range and lock-in range are 400kHz and 48kHz, respectively. This scheme shows the potential of using lasers to generate tunable phaselocked narrow linewidth optical comb carriers for SCM and FDM optical communication systems or optical-controlled microwave phase array antennas.

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Satellite coupler: Application to distributed star network

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Indexing terms: Optical couplers, Star couplers

The authors describe a method for multiplying the port number of interconnectable star couplers. The insertion loss of a 12 port singlemode interconnectable star coupler is calculated as 16.9dB. The method is applicable to a new distributed star network which reduces the required gain of the optical amplifier by 7.4dB.

Introduction: Recently, there have been some reports on networks constructed by directly connecting star couplers. Networks constructed with conventional star couplers using sophisticated connection methods were reported in [1, 2]. Networks using interconnectable star couplers and simple connection methods were reported in [3–8]. The direct connection of star couplers involving optical amplifiers, was reported in [2, 5, 7, 8]. Star couplers having more terminals are preferred for many applications.

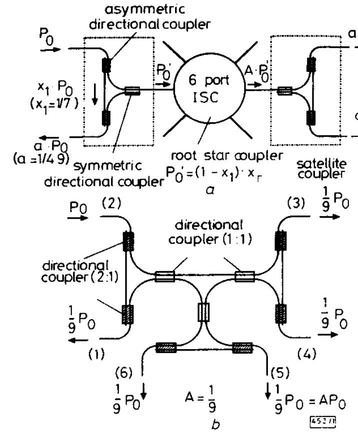

Fig. 1 *Method to multiply port number of interconnectable star coupler (6 port → 12 port)*

a Connection of satellite couplers
b Structure of 6 port interconnectable star coupler

Multiplication method: Fig. 1*a* shows a method for doubling the port number of a 6port singlemode interconnectable star coupler (ISC). Satellite couplers are connected to the root interconnectable star coupler. The satellite coupler consists of two asymmetric directional couplers and one symmetric directional coupler as shown in Fig. 1*a*. The internal structure of a 6port interconnectable star coupler [7] is shown in Fig. 1*b*.

As described in a previous paper [7], the distribution ratio of an asymmetric directional coupler x_1 is derived as follows:

$$a = x_1^2 \qquad (1)$$

$$a = (1 - x_1)^2 x_r^2 A \qquad (2)$$

where a, x_r and A are the insertion loss (transmission coefficient) of a 12port interconnectable star coupler, distribution ratio of a