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Multi-wavelength source using low drive-voltage amplitude modulators for optical communications

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Abstract: A simple and cost-effective technique for generating a flat, square-shaped multi-wavelength optical comb with 42.6 GHz line spacing and over 0.5 THz of total bandwidth is presented. A detailed theoretical analysis is presented, showing that using two concatenated modulators driven with voltages of 3.5 V_π are necessary to generate 11 comb lines with a flatness below 2dB. This performance is experimentally demonstrated using two cascaded Versawave 40 Gbit/s low drive voltage electro-optic polarisation modulators, where an 11 channel optical comb with a flatness of 1.9 dB and a side-mode-suppression ratio (SMSR) of 12.6 dB was obtained.

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References and links

1. S.C. Zeller, G.J. Spuhler, L. Krainer, R. Paschotta, U. Keller and K.P. Hansen, "Frequency comb generation with 50-GHz channel spacing in the telecom C-band" Tech Dig. CLEO'05, San Francisco, 2005, pp. 221.
2. J. Capmany, D. Pastor and B. Ortega, "Microwave signal processing using optics", Tech Dig. OFC'05, Anaheim, 2005, pp. 23-76.
3. J. Azana, N.K. Berger, B. Levit, W. Smulakovsky and B. Fischer, "Broadband arbitrary waveform generation based on microwave frequency upshifting in optical fibers", IEEE J. Lightwave Tech., **24,** 2663-2675 (2006).
4. A.D. Ellis, F.C. Garcia-Gunning and T. Healy, "Coherent WDM: The achievement of high spectral density through phase control within the transmitter", Tech. Dig. OFC '06, Anaheim, 2006, OThR4.
5. F.C. Garcia-Gunning and A.D. Ellis, "Generation of widely spaced optical frequency comb using an amplitude modulator pair," in Proc. SPIE - Opto-Ireland Symposium 5825B-74, pp. 469-474, (2005).
6. S. Yamashita and G.J. Cowle, "Bidirectional 10-GHz Optical Comb Genereation with an Intracavity Fiber DFB Pumped Brillouin/Erbium Fiber Laser", IEEE Phot. Tech. Lett., **10**, pp. 796-798, (1998).
7. S. Gee, F. Quinlan, S. Ozharar, P.J. Delfyett, J.J. Plant and P.W. Judoawlkis, "Optical Frequency Comb Generation from Modelocked Diode Lasers – Techniques and Applications" Digest of the LEOS Summer Topical Meetings, pp. 71-72, (2005).
8. T. Sakamoto, T. Kawanishi and M Izutsu, "Optoelectronic oscillator using a $LiNbO_3$ phase modulator for self-oscillating frequency comb generation" Opt. Lett., **31**, pp. 811-813, (2006).
9. H. Takara, T. Ohara, K. Mori, K. Sato, E. Yamada, Y Inoue, T. Shibata, M. Abe, T Morioka and K-I. Sato, "More than 1000 channel optical frequency chain generation from single supercontinuum source with 12.5GHz channel spacing" Electron. Lett., **36**, pp. 2089-2090. (2000),
10. M. Fujiwara, M. Teshima, J. Kani, H. Suzuki, N. Takachio and K. Iwatsuki, "Optical carrier supply module using flattened multicarrier generation based on sinusoidal amplitude and phase hybrid modulation", IEEE J. of Lightwave Tech., **21**, pp. 2705-2714, (2003).

#78121 - $15.00 USD Received 14 December 2006; accepted 13 February 2007

11. J.J. O'Reilly, P.M. Lane, R. Heidemann and R. Hofstetter, "Optical generation of very narrow linewidth millimetre wave signals", Electron. Lett., **28**, pp. 2309-, (1992)
12. Q. Chen and X. Guan, "Spectrum analysis of phase amplitude modulation", IEEE Transactions on Broadcasting, **36**, pp. 34-36, (1990).
13. J.D. Bull, N.A.F. Jaeger, H. Kato, M. Fairburn, A. Reid and P. Ghanipour, "40 GHz electro-optic polarization modulator for fiber optic communications systems," Proc. SPIE, **5577**, pp. 133-143, (2005).

1. Introduction

In recent years multi-wavelength generation (also called multi-frequency or comb generation) has attracted interest for use in a number of areas in photonics technology. For example, in optical communications ultra-dense wavelength division multiplexing (UD-WDM) uses tightly spaced optical channels (<50 GHz spacing) generated from spectrally sliced optical combs to transmit data in both access and long-haul networks requiring large channel counts, and Zeller et al suggested that optical combs generated from mode-locked lasers are suitable sources for test and measurement of DWDM systems [1]. Optical combs are also finding application in the microwave regime where they have been used to implement photonic microwave filters [2], and the frequency up-shifting of arbitrary microwave waveforms [3], where tunability is a key parameter. More recently a novel optical transmission format, known as Coherent Wavelength Division Multiplexing (CoWDM) [4], has been proposed, which relies on a stable phase relationship between adjacent channels [5]. Choosing an optimum comb generation technique clearly involves application dependent performance trade-offs.

In this paper we consider the application of optical combs to CoWDM. There are numerous benefits of using a comb generator in such optical transmitters including a reduction in the number of laser sources and wavelength lockers required, and an increase in the attainable spectral density. When evaluating the merits of various comb generation techniques for this application it is important to consider the following key parameters which define overall performance. Firstly, high power conversion efficiency including component insertion losses, power lost to unwanted sidebands and in attenuation of high power channels to produce a uniform power distribution which is not degraded by subsequent optical filtering. Meeting this requirement necessarily requires a square shaped comb, with uniform amplitudes for the wanted comb lines, and excellent intrinsic suppression of unwanted comb lines. Secondly, it is important for some applications (e.g. CoWDM) to have well defined line spacing and a stable phase relationship between comb lines. Finally, a simple and cost effective configuration is desired.

Previously reported comb generation techniques include (1) the use of amplitude or frequency modulated (FM) mode-locked lasers (such as ERGO (Er:Yb:glass laser oscillator) lasers [1], fibre ring lasers [6], or mode-locked semiconductor lasers [7]), which give good optical signal-to-noise ratio (OSNR) values, but require precise control of the laser cavity length; (2) a wideband LiNbO3 phase modulator in self-oscillating mode [8] when driven with a feedback signal from its output, which makes oscillation easier to start and maintain than mode-locked lasers, but requires large RF power amplifiers with precise control of the output voltage, in addition to extra filters and photodiodes; (3) an amplitude modulator with a section of highly non-linear fibre [9], which also results in a good OSNR, but needs high optical launch powers, long fibre lengths and stimulated Brillouin scattering (SBS) suppression; and (4) concatenated Mach-Zehnder (MZ) and phase modulators [10], a method which gives good uniformity across the channels, but requires the use of large drive voltage amplifiers and precise control of the applied voltage. Techniques (1) and (2) generally require an appropriately shaped optical filter to produce reasonable flatness, whilst (3) produces a large number of unwanted comb lines; in each of these cases the power efficiency of the comb is reduced.

In this paper we present an analysis of the production a phase locked optical comb using two cascaded amplitude modulators. We also demonstrate a practical implementation of the scheme, where an 11 channel, 468 GHz bandwidth comb is generated using two 40 GHz electro-optic polarisation modulators with low drive voltages. It is shown that the additional tuning freedom offered by replacing the phase modulator of (4) by a second amplitude modulator allows excellent flatness (<2 dB) and high SMSR values (>12 dB) without the need to precisely tune RF amplitudes, whilst the low drive voltage electro-optic polarisation modulators enable us to maintain a modest RF power level.

2. Theoretical Investigation

The proposed comb generation module is shown in figure 1, and comprises a single DFB laser source at 1546.8nm, and two sine wave driven balanced electro-optic modulators.

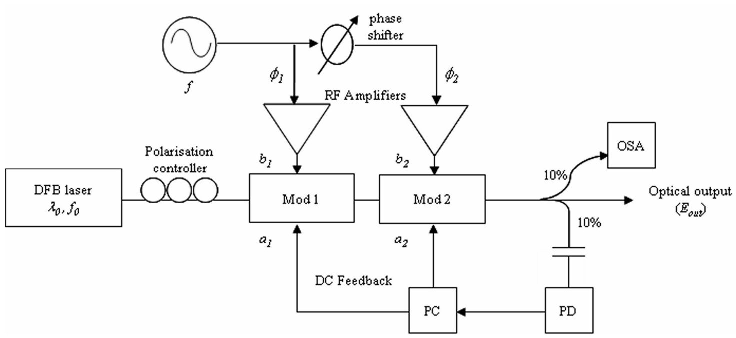

Fig. 1. Schematic diagram of comb generator experimental configuration

It is well known that for a continuous wave input with frequency f_0, amplitude E_0 and phase ϕ_{in}, the output optical field E_k of the k^{th} modulator can be represented as a series of harmonic frequency components f_0+pf where f_0 is the optical carrier frequency, f is the frequency of the sine wave drive, and p represents the harmonic number, $p\in\{0, \pm1, \pm2,\ldots\}$[11]. The total field E_k is given by

$$E_k = |E_0| \sum_p \varepsilon_p, \quad \varepsilon_p = A_{p,k} cos\left[2\pi(f_0 + pf)t + \theta_{p,k}\right] \tag{1}$$

where the amplitudes $A_{p,k}$ and phases $\theta_{p,k}$ of the components are given by

$$A_{p,k} = \frac{1}{2} cos[(a_k + p)\frac{\pi}{2}] J_p(\frac{b_k \pi}{4}), \quad \theta_{p,k} = [1 + p + (-1)^p]\frac{\pi}{2} + p\phi_1 + \phi_{in} \tag{2}$$

In both equations, a_k, b_k and ϕ_k represent the DC offset, peak-to-peak amplitude, and phase of the drive signal of the k^{th} modulator respectively, and J_p is the Bessel function of the first kind of order p. By considering each component generated from the first modulator as CW input to the second, and summing all of the terms which result in an output from the second modulator at a given harmonic frequency component f_0+qf we obtain the total output field (E_{out}) from the second modulator. Assuming, without loss of generality, that this results in a total output field (E_{out}) of

$$E_{out} = |E_0| \sum_q \varepsilon_q' \tag{3}$$

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$$\varepsilon_q' = \frac{1}{2}\sum_p A_{p,1}\left\{\left[(-1)^{2p-q} A_{p-q,2} + (-1)^q A_{q-p,2}\right]\cdot\right.$$

$$\left.\cdot\cos\left[2\pi\left(f_0 + qf\right)t + q\frac{\pi}{2} + (q-p)\phi_2\right]\right\} \quad (4)$$

We can see from Eq. (1) and Eq. (4) that the RF amplitudes ($b_{1,2}$), DC bias ($a_{1,2}$) and relative phase difference (ϕ_2) between the RF drive signals may be used to control the relative amplitudes of each comb line, giving excellent control of the profile of the generated comb signal. In particular, we may use these five variables to solve a set of five simultaneous equations matching the amplitudes of the first five harmonics to the central carrier component ($\varepsilon_0=\varepsilon_q$, $q=0, 1, 2, 3, 4, 5$). Given the inherent symmetry of the system $\varepsilon_q=\varepsilon_{-q}$ this implies that ideally an 11 channels comb could be generated with 0 dB power variation. Note that, if one of the amplitude modulators is replaced by a phase modulator [12], the cosine term, along with the term $(-1)^p$ is omitted from Eq. (2), thus reducing by one the number of control parameters available.

Figure 2 illustrates, for various numbers of comb lines, the calculated power variation (flatness) of the side-bands when the same RF power (b_k) is applied to both modulators simultaneously and the RF phase and DC biases are optimised for each point. Under these restrictive conditions negligible power variation is obtained for up to 11 comb lines, whilst a flatness of less than 2 dB is obtained for up to 13 comb lines. It is interesting to note that total bandwidths of close to or above 0.5 THz can be obtained with this method, whilst maintaining a good flatness and that by tuning the RF amplitudes to 4.37 and 4.45 V_π ideal flatness may be achieved.

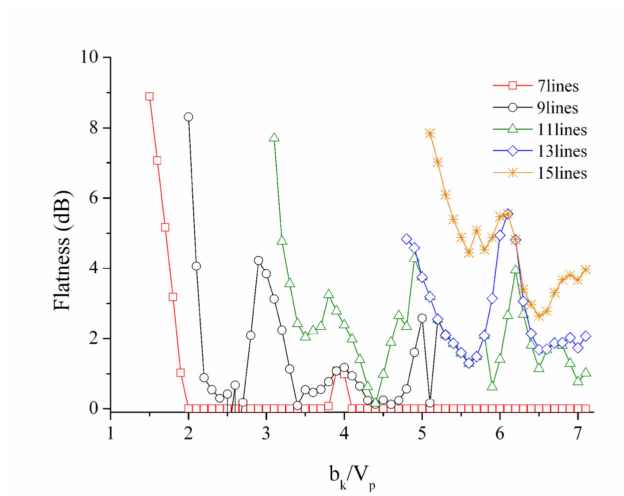

Fig. 2. Optimised comb flatness versus relative drive amplifier amplitude for 7 (squares), 9 (circles), 11 (triangles), 13 (diamonds) and 15 (star) comb lines.

A more detailed analysis of the impact of the RF amplitudes on flatness for a comb of 11 lines is shown in figure 3. In this case, b_k was set independently for each modulator, while the DC biases and relative optical phases were optimised. It is clear that whilst voltages above 3.5 V_π are necessary in order to achieve good flatness, values of less than 1 dB are possible for a wide range of drive voltages, eliminating the need for controlled drive amplitudes, suggesting that the comb can be controlled by a_1, a_2 and ϕ_2 alone. For target RF values of around 4.5 dB, almost ideal flatness of 0 dB may be obtained, again with a reasonable tolerance to the drive signal amplitudes. The point marked with a circle on figure 3 represents the experimental operating position, as described below, with a flatness of less than 2 dB.

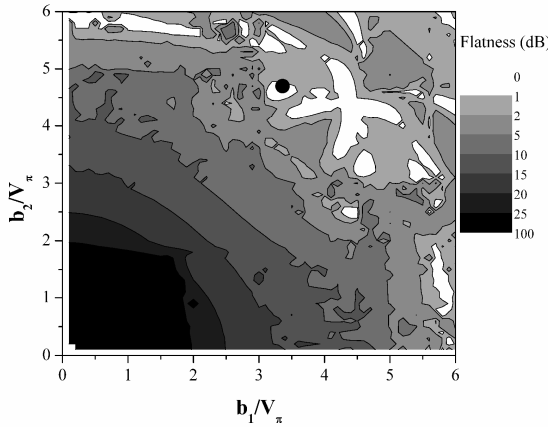

Fig. 3. Optimised comb flatness versus drive voltage applied to each modulator for 11 lines.

3. Experimental Configuration

The two 40 Gbit/s Versawave electro-optic polarisation modulators were driven with a sine wave of frequency f = 42.6 GHz, and amplitudes b_1 = 3.36 V_π and b_2 = 4.70 V_π, synchronised by an RF delay line. The modulators were based on GaAs polarisation mode converters, with low V_π (3.3 V and 3.7 V at 20 GHz), low insertion loss (4.3 dB and 6.0 dB), and 3 dB bandwidths of 31 GHz and 49 GHz respectively. The combination of a wideband frequency response and low V_π enables a significant increase in the number of generated comb lines without an increase in RF power levels in comparison to typical LiNbO3 modulators. The low drive voltage of the GaAs mode converter results from the tight mode confinement that is possible with etched semiconductor waveguides, while the high bandwidth results from low-loss, velocity matched slow-wave electrodes [13]. A further advantage of GaAs over LiNbO3 for high-power applications is that GaAs has much higher thermal conductivity (55 vs. 5.6 $Wm^{-1}K^{-1}$), potentially increasing the reliability during high power operation. This configuration yields a compact and square-shaped-like 11 lines optical comb, as shown in figure 4.

The flatness achieved was 1.97 dB which is higher than the theoretical prediction (figure 3) of less than 1dB. We believe this is due to features of the experimental setup such as the large amount of fibre between the two modulators which causes the optical phase to drift during the measurement. A value of 12.6 dB was obtained for the SMSR of the optical comb. Moreover, this setup also provides a phase coherent comb, suitable for CoWDM applications, where each comb line could be independently modulated at 42.6 Gbit/s, enabling almost 0.5 Tbit/s of capacity using only one DFB laser.

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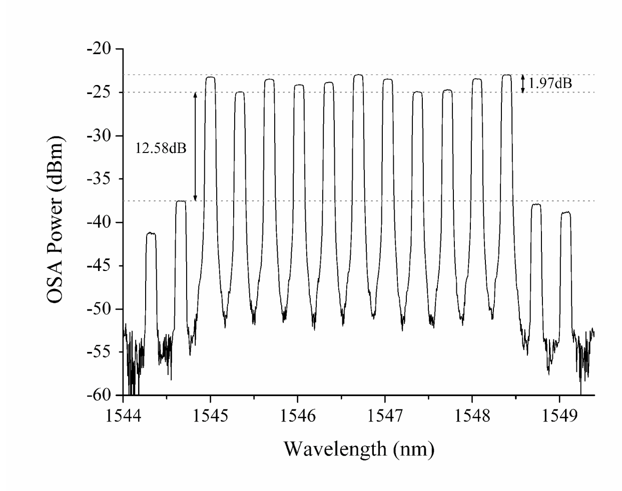

Fig. 4. Experimental spectrum of an 11 channel optical comb.

As with all applications of amplitude modulators, a degree of feedback control is necessary in order to compensate for thermally induced bias point and RF power level drifts. Observing from Eq. (1) that, for small drifts in parameters a_k and b_k, the impact of each modulator may be effectively controlled by the DC bias a_k alone, we implemented a simple stabilisation circuit whereby the comb output is monitored using a scanning Fabry-Perot filter (FSR = 13.7 THz, RBW = 6.1 GHz) and a low bandwidth photodiode in order to provide feedback to the DC bias controls. This enabled stable comb performance over a period of several hours.

4. Conclusions

In summary, we have reported a simple technique for generating a stable power efficient square-shaped 11 channel optical comb with good flatness (<2 dB) and SMSR (>12 dB) values. Theoretical results were presented showing the variation in comb flatness over a range of applied RF power levels suggesting that 13 lines (553 GHz total bandwidth) may be obtained with flatness better than 2 dB. For 11 comb lines (468 GHz total bandwidth), the optimum comb flatness predicted from the theory agrees well with the experimental results. The enabling components for applying this method of comb generation experimentally were two low drive voltage modulators, i.e. Versawave electro-optic polarization modulators. The comb channels are spaced by 42.6 GHz and are phase locked to each other, which makes this comb generation technique suitable for use with a broad range of applications including CoWDM.

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