Performance analysis of optical prefiltering-SCM systems by accurate spectral techniques*

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Abstract

We present a detailed study of the DC optical prefiltering (OP) technique in subcarrier multiplexed (SCM) lightwave systems. A numerical model, including all of the most relevant limiting effects, is used in combination with Prony's method in order to obtain an accurate assessment of analog transmission systems performance. Intrinsic limitations of the DC-OP technique are highlighted and the full numerical results are compared with those obtained from limited analytical approximations.

1 Introduction

Optical prefiltering (OP) in subcarrier multiplexing (SCM) optical transmission was first demonstrated experimentally in 1992 [1]. While having some technical complexities, DC-Optical prefiltering presents two important advantages: [2, 3] (a) Less severe effect of the fiber dispersion-induced distortion, which imposes a strong and fundamental limit for the fiber length in standard SCM links; and (b) simplicity of the optical receiver, which becomes a "universal receiver" in that the SCM band may be extended or changed without affecting at all the users' receivers.

The previous works on DC-OP have been more concerned with experimental demonstrations in "ideal" conditions (see, for example, [4]). Realistic analytical modeling of DC-OP is virtually impossible due to the huge complexity of the resulting algebra.

In this paper we shall use Prony's method to compute the harmonic and interharmonic distortion ratios in a DC-OP SCM system operating under several circumstances (sec. 3). We already showed this method to be a powerful and efficient tool for a similar purpose in another context [5].

*Manuscript of the article published in IEEE Trans. on Photonics Technology Letters, vol 12, no. 1 (2000).

2 Improved Approximate Analytical Approach

The DC-OP system is schematically represented in Fig. 1. Prior to detection, a piezoelectric tunable filter is used to select one of the subcarriers. To be specific, we shall consider a standard Fabry-Perot (FP) cavity.

In an SCM system, assuming that the laser source is completely linear and disregarding the distorsive properties of the fiber, the (analytical) field at the filter input has the form

$$E_{\rm in}(t) = P_0^{1/2} \left[1 + m \sum_{k=1}^{N} s_k(t) \cos(\omega_k t) \right]^{1/2} e^{i\omega_0 t}\, \xi(t), \tag{1}$$

where P_0 is the power of the optical carrier, N is the number of subcarriers, ω_k and $s_k(t)$ are the k-th RF or microwave subcarrier frequency and modulating signal, respectively, ω_0 is the optical frequency, and $\xi(t)$ represents the complex envelope of the optical carrier, which amounts for the non-monochromaticity of the laser (assumed chirpless for now). The optical modulation index, m, is taken to be the same for all the subcarriers. A necessary assumption to obtain tractable results is $mN << 1$, so that the square root may be approximated by two terms. The photocurrent at the photodetector output will be proportional to $\langle E^*_{\rm out}(t) E_{\rm out}(t) \rangle$, where $\langle \cdot \rangle$ denotes time-averaging over enough optical periods. Such an operation produces, among others, the "DC" component, which bears no subcarrier oscillations, but just a DC value modulated by the slowly-varying signals $s_k(t)$. It is this component that the DC-OP systems make use of.

An oversimplified expression for the DC photocurrent was given in [2] using straightforward approximations which yield little more than the FP filter function itself. By using a judicious approximation of the FP filter response, we shall reach further insight into the system operation. The photocurrent is found to be, for a perfectly monochromatic laser and a FP filter tuned at $\omega_0 + \omega_1$,

$$\begin{aligned} i_{\rm DC}(t) \simeq \Re P_0 \Bigg\{ & F_{-0} + \frac{m^2}{16} s_1^2 \left(t - T - \tau_1\right) \\ & + \frac{m^2}{16} s_1^2 \left(t - T + \tau_2\right) F_{-1} \\ & + \frac{m^2}{16} \sum_{k=2}^{N} s_k^2 \left(t - T + \tau_2\right) \left(F_k + F_{-k}\right) \Bigg\}, \end{aligned} \tag{2}$$

with T the FP filter transit time, $\tau_1 = 2r^2T/(1-r^2)$, $\tau_2 = 2r^2T/(1+r^2)$ and $F_j = \left(1-r^2\right)^2 / \left[1 + r^4 - 2r^2 \cos[(2\omega_0 + {\rm sign}[j]\, \omega_{|j|})T\right]$.

To obtain (2), the amplitude response of the FP filter is taken approximately constant within the signal bandwidth and the phase response is approximated with a linear piecewise response. In equation (2) we find a constant term due to the filtered optical carrier (F_{-0}), a crosstalk term (sum over k) and two components corresponding to the desired signal, $s_1(t)$, one due to the upper sideband of the optical spectrum, where the FP filter is tuned, and the other to the lower sideband.

One of the major drawbacks of the OP scheme when used for analog transmission is the intrinsic quadratic distortion present in the received signal. If we consider, for simplicity, one single subcarrier frequency, ω_1, and assume it is AM-modulated by an analog signal: $s(t) = 1 + m_s x(t)$, with a pure tone of frequency Ω within the video band, $x(t) = \cos(\Omega t)$, then

$$i_{\mathrm{DC}}(t) = \Re P_0 \left\{ \left[A + \frac{m^2}{16}\left(1 + \frac{m_s^2}{2}\right)\right] + \right. \\ \left. + \frac{m^2 m_s}{8}\left[\cos\left(\Omega(t-t_0)\right) + \frac{m_s}{4}\cos\left(2\Omega(t-t_0)\right)\right]\right\}, \tag{3}$$

where A is a constant term and $t_0 = T + 2r^2T/(1-r^2)$ is the group delay introduced by the FP filter at resonance. The second harmonic distortion can be expressed as $-20\log(m_s/4)$ and is independent of the modulation depth of the optical carrier. If this value is to be kept below 60 dB, a typical quality requirement for AM transmission, a value of m_s for a subcarrier modulation below the 0.4% is needed. One could increase the value of m while keeping m_s below the threshold for the desired second order distortion, but the value of m has to be limited in order to control the effect of clipping.

The use of signal predistortion is technically well justified for broadcast networks. If $s(t) = (1 + m_s x(t))^{1/2}$, the received signal is free of distortion, as can be easily checked in (3) and numerically verified with the method presented in Section 3.

3 Full Numerical Approach. Results

The analysis presented so far is based on a series of simplistic assumptions, such as $mN << 1$. This assumption can be easily violated, for example, when the total number of channels is high. Also, laser nonlinearities, fiber dispersion or FM-AM modulation as a result of frequency chirp when using direct modulation of a semiconductor laser, which is the most common case so far, have been neglected.

Large signal modulation conditions will be assumed in the following. The frequency chirp will also be included in the analysis, since this effect will be responsible, to the highest order, of optical beat interference in our system. On the other hand, systems based on optical prefiltering are known to be robust against the phase distortion of the optical signal when propagating in the fiber, and we shall not consider it since it is not relevant for the results.

We consider the intensity modulation of an optical signal including the effect of clipping. The optical field at the output of the transmitter is then given by the expression

$$E(t) = \sqrt{P(t)}\exp\left[i\omega_0 t + \phi(t)\right] \tag{4}$$

where $\phi(t) = (\beta_c/2)\log[P(t)/P(0)]$ is the phase modulation accompanying the intensity modulation of the laser. [6]

The detected photocurrent, corresponding to the video signal, is obtained from $i_{DC} = \mathrm{DC}\left\{|\mathrm{OF}\{E(t)\}|^2\right\}$ where the operator "DC" corresponds to low-pass electrical filtering to a single channel bandwidth, and "OF" is the optical filtering at the receiver front end.

We now describe the technique used to realistically compute the detected photocurrent with the DC-OP system. To highlight the essential features without unsubstantially complicating the presented results, it will suffice to consider only three subcarriers (chosen to lie within an octave to prevent 2nd order intermodulation). The filter parameters will be adjusted so as to pick one of the subcarriers, and the intermodulation caused by the other two will be calculated. In such a DC system, the only way to achieve this is to, in turn, modulate each subcarrier with a sinusoidal envelope of different frequency, and resolve the sinusoidal components in the output photocurrent. Prony's method tries to fit a given discrete sequence to a model taken as a sum of complex exponentials with unknown frequencies and amplitudes.

Several degrees of complexity will be considered.

Let us first assume an ideal *monochromatic chirpless* laser.

We take (1) with $N = 3$ and $s_k(t) = 1 + m_s \cos(\Omega_k t)$. A Fabry-Perot filter, with $FSR = 10$ GHz and $F = 100$, is adjusted to select the ω_1 subcarrier. A judicious choice of the envelope frequencies Ω_k must be done. If we took, for example, $\Omega_2 = 2\Omega_1$, the spectral power occurring at the frequency Ω_2 would stem from the interferent second harmonic of the sinusoidal envelope of the ω_1 subcarrier and the quadratic distortion suffered by the envelope of ω_2 itself; the latter effect masks the former and should be avoided. This forces to choose the Ω_k such that (preventing interference up to third order) $\Omega_i \pm \Omega_j \neq \pm\Omega =_k$ and $\Omega_i \pm \Omega_j \pm \Omega_k \neq \pm\Omega_l$.

However, note that $\omega_1 = 2\omega_2 - \omega_3$; this was made intentionally, with the solely purpose to analyze the worst case for intermodulation crosstalk due to the contribution of the composite triple order (CTO) term.

Figure 2 shows the signal level of the subcarrier ω_1. The $\sim m^2$ dependence predicted by (2) saturates as m increases, thus showing the failure of the analytical model (which is derived assuming very small values of m). However, there is no deviation from the linear dependence with m_s, which is not an optical parameter.

Figure 3 presents the second harmonic distortion (SHD) level for the selected signal. The results are in good agreement with the simplified theoretical model, which predicts a relation between the SHD and the signal amplitudes of $m_s/4$ (independent of m), for low values of m. A deviation from this behavior is observed for larger m, where the $mN \ll 1$ approximation used in (2) is clearly violated.

Figure 4 shows the crosstalk from the signal modulating the subcarrier at ω_2, with and without chirp. The result obtained from the simplified theoretical analysis (2) shows equal dependences on both m and m_s (implicit in the definition of $s(t)$) for the selected signal and the crosstalk terms. With the approximations used, the crosstalk would be only due to the finite selectivity of the optical filter and constant when either m or m_s vary. Figure 4 reveals a strong dependence with m even in the absence of chirp, which shows the violation of the two-term approximation used in (2). On the other hand, the crosstalk is almost independent of m_s, as before. With chirp (we have taken a typical value of $\beta_c = 5$), the crosstalk strongly increases due to the high interference generated in the FM-AM modulation process. The effect of the predistortion scheme has not been shown because it does not virtually affect the system crosstalk.

Finally, the finite laser linewidth can be accounted for by generating a suitable Wiener process. We took a typical bandwidth of 100 MHz (FWHM). The results, not displayed for the sake of brevity, simply yield slightly "noisy" curves of which the noisless curves shown thus far are just their average. This is intuitively expected and shows that, provided the linewidth of the optical source does not make the subcarriers overlap, the laser nonmonochromaticity is not a serious limitation. The inclusion of the laser nonlinearity (which we have neglected in favor of the clipping) and other refinements would be straightforward in our model.

4 Conclusions

We have presented a powerful method to evaluate the performance of DC-OP SCM systems with many features realistically accounted for. The obtained results reveal the limitations of previous models, but show the feasibility of the DC-OP SCM systems even with non-highly coherent sources. Our method could be easily applied to other OP SCM schemes.

Acknowledgments

The authors wish to acknowledge financial support from the Spanish CICYT via project TIC-95-0859-C02-02.

Figure captions

Figure 1. Block diagram of an SCM optical communication system using optical prefiltering in the receiver.

Figure 2. The variation of detected signal level (in arbitrary units) with the optical modulation index m for different subcarrier modulation indexes m_s. It is also included the analytic result as given by (2).

Figure 3. Second harmonic distortion in terms of the subcarrier modulation index m for different optical modulation indexes m.

Figure 4. The crosstalk between the subcarrier at ω_1 and at ω_2 in terms of the subcarrier modulation index for different optical modulation indexes.

References

[1] P. A. Greenhalgh, R. D. Abel, and P. A. Davies, “Optical prefiltering in subcarrier systems,” *Electron. Lett.,* vol. 28, pp. 1850-1852, 1992.

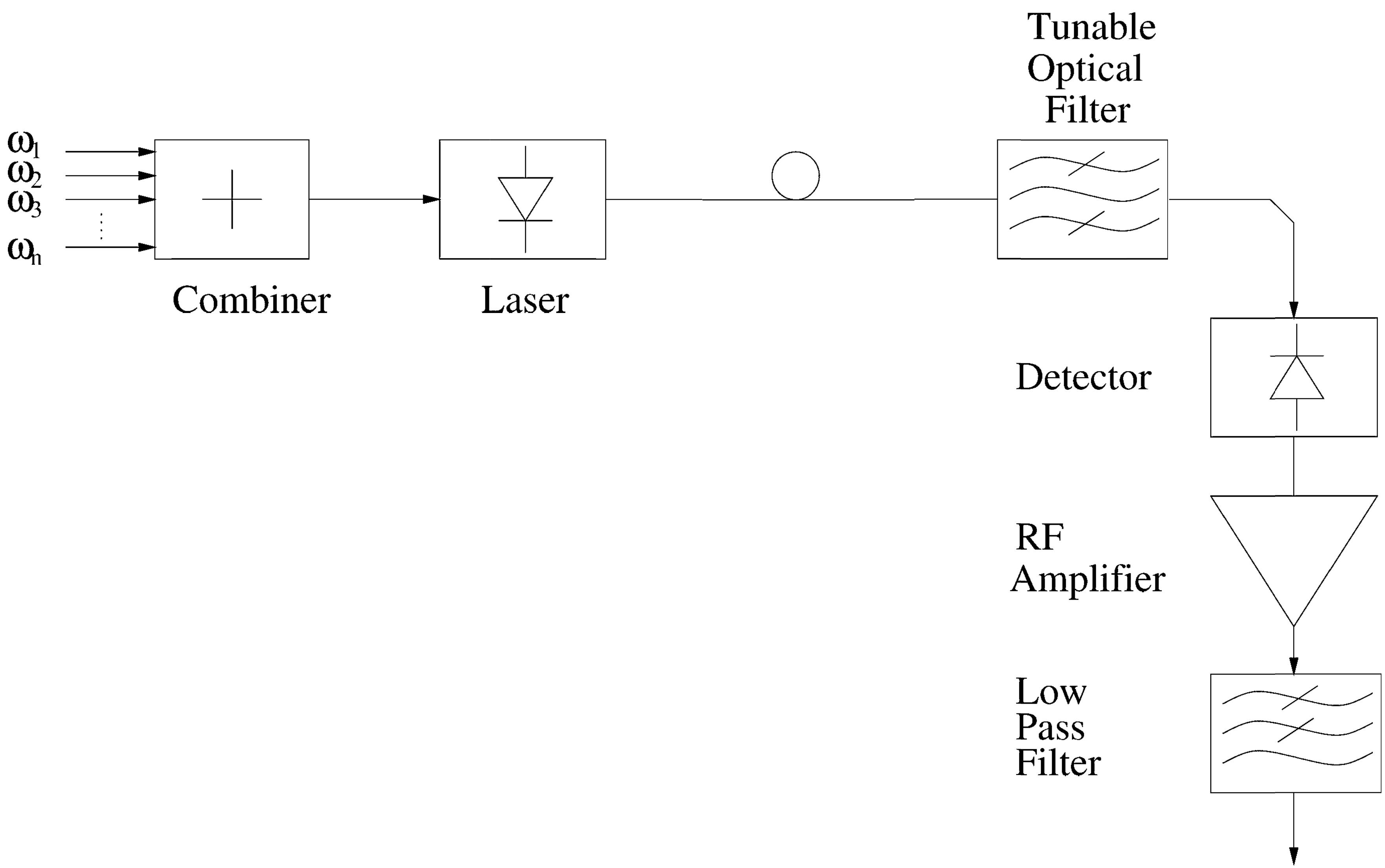
[2] J. Marti and J. Capmany, “Modelling optically prefiltered AM subcarrier multiplexing systems,” *IEEE Trans. Microwave Theory and Techn.,* vol. 43, pp. 2249-2256, 1995.

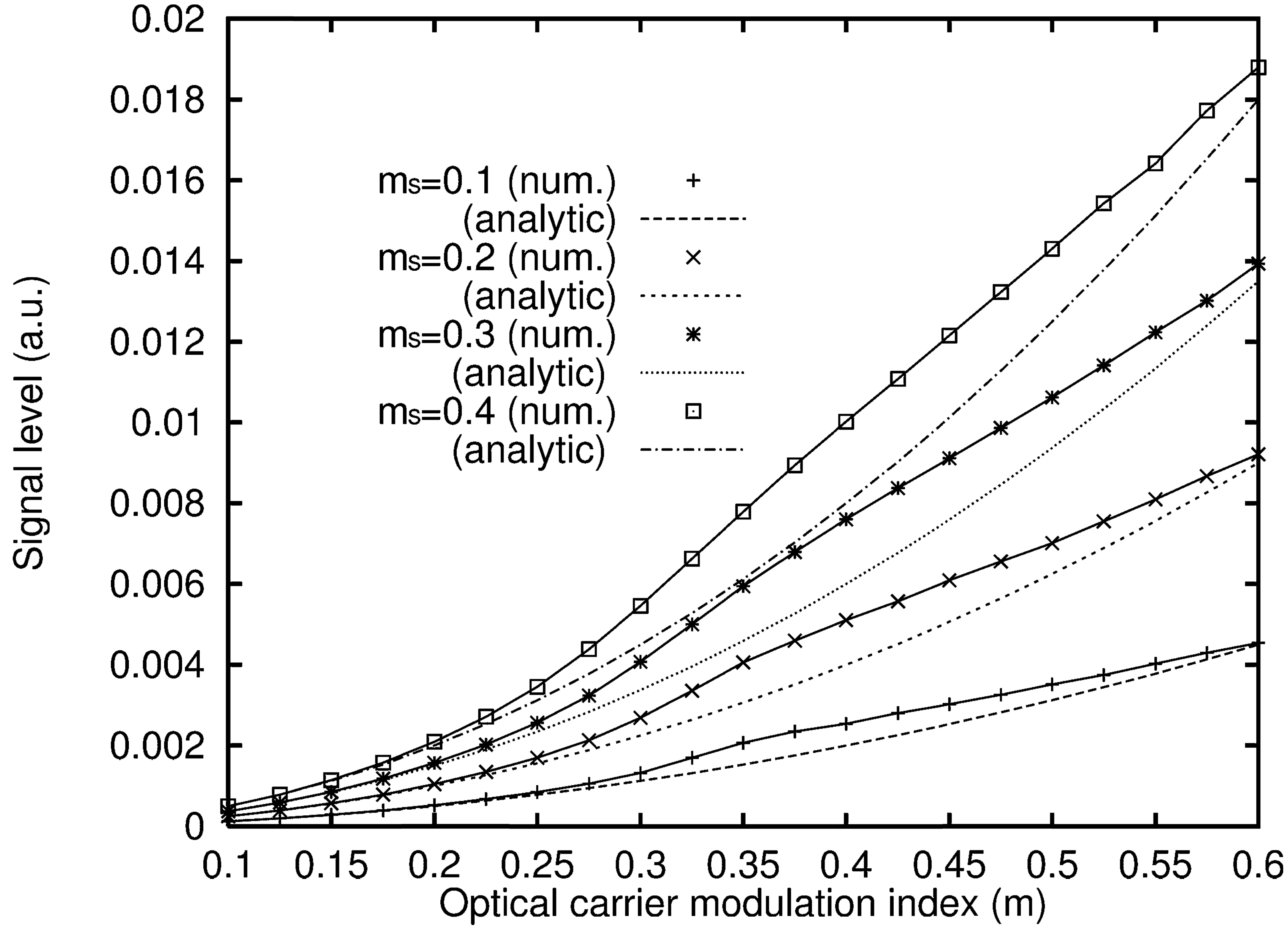
[3] P. D. Sargis, R. E. Haig, K. G. McCammon, and S. Young, “Subcarrier multiplexing with dispersion reduction,” *Electron. Lett.,* vol. 31, pp. 1769-1770, 1995.

[4] J. Capmany, D. Pastor, A. León, P. Chamorro and D. Santos, “Experimental demonstration of optical prefiltering in WDM-SCM optical networks employing an ultraselective optical bandpass filter”, *Electron. Lett.*, vol. 35, pp. 318-319, 1999.

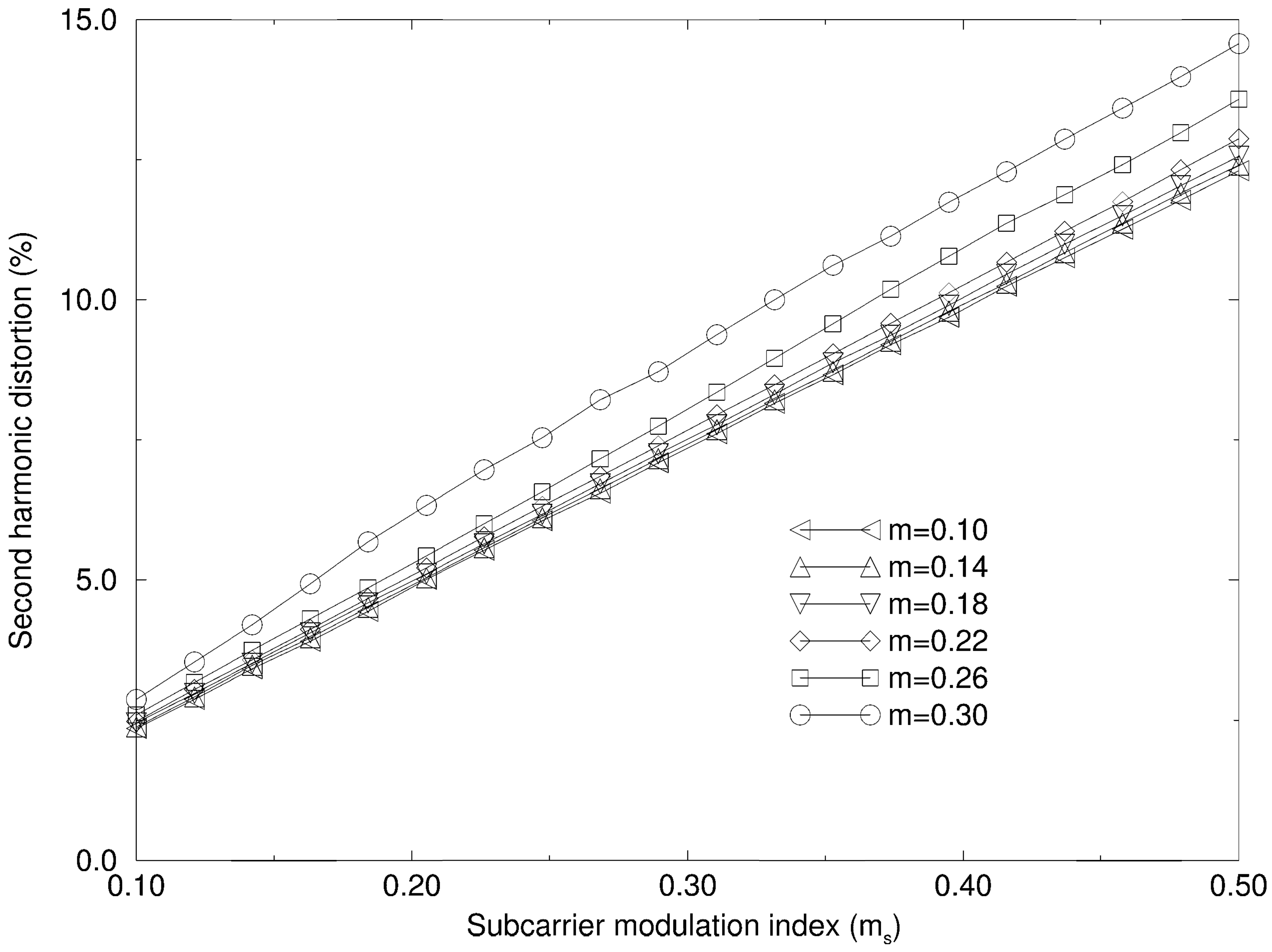
[5] P. Chamorro-Posada, R. Gómez-Alcalá and F.J. Fraile-Peláez, “Modal analysis of optical waveguides using Prony’s method and BPM”, *Microwave and Opt. Tech. Lett.*, Vol. 7, pp. 529–532.

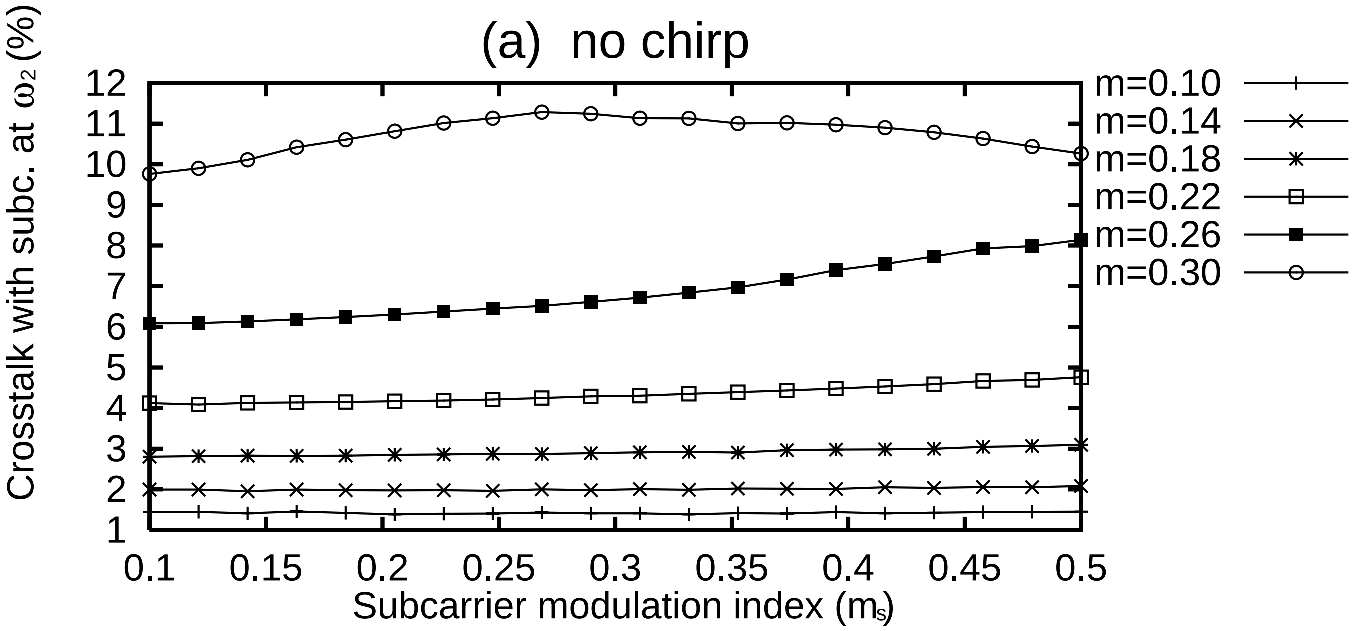
[6] G. P. Agrawal and N. K. Dutta, *Semiconductor Lasers*, 2nd Ed. New York: Van Nostrand Reinhold, 1993, pp. 250-288.

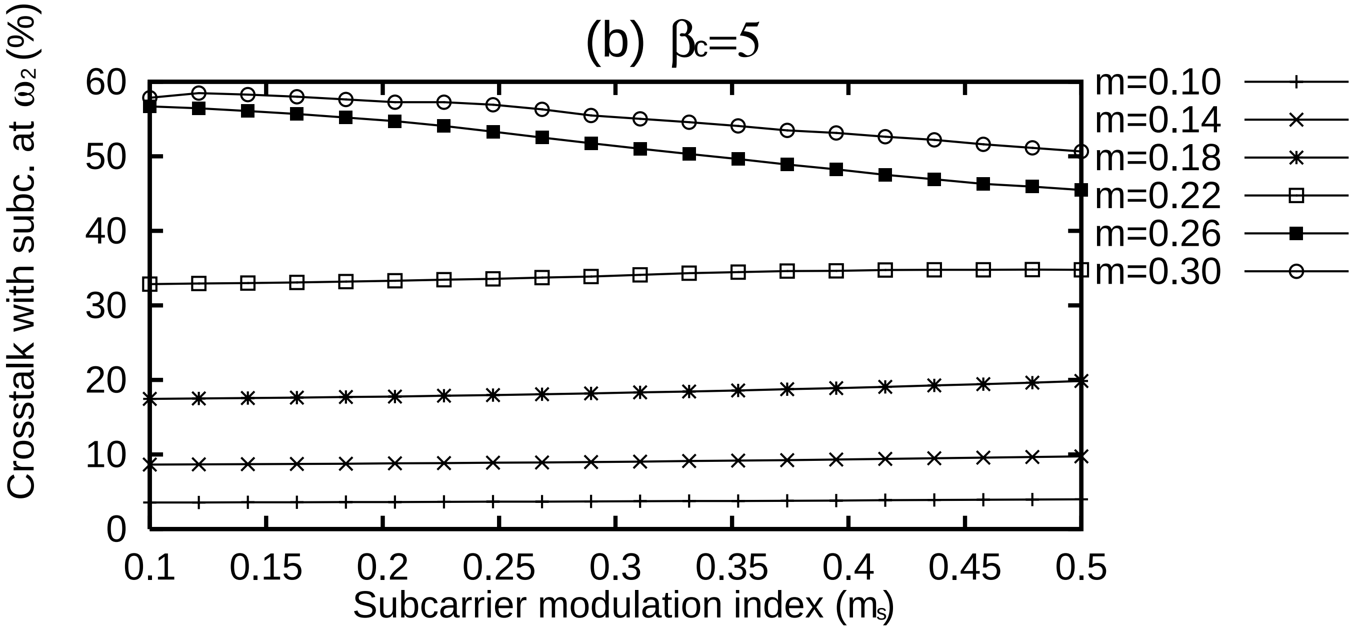

ω1
ω2
ω3
ωn
Combiner
Laser
Tunable Optical Filter
Detector
RF Amplifier
Low Pass Filter



ms=0.1 (num.)
(analytic)
ms=0.2 (num.)
(analytic)
ms=0.3 (num.)
(analytic)
ms=0.4 (num.)
(analytic)
Signal level (a.u.)
Optical carrier modulation index (m)
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6


Second harmonic distortion (%)
0.0
5.0
10.0
15.0
0.10
0.20
0.30
0.40
0.50
Subcarrier modulation index (m_s)
m=0.10
m=0.14
m=0.18
m=0.22
m=0.26
m=0.30


(a) no chirp
Crosstalk with subc. at ω2 (%)
Subcarrier modulation index (ms)
m=0.10
m=0.14
m=0.18
m=0.22
m=0.26
m=0.30


(b) βc=5
Crosstalk with subc. at ω2 (%)
Subcarrier modulation index (ms)
m=0.10
m=0.14
m=0.18
m=0.22
m=0.26
m=0.30