Subcarrier Homodyne De-multiplexing Scheme for SCM Optical Communication Systems

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Abstract

A subcarrier de-multiplexing scheme has been proposed for SCM optical communication systems, in which a pair of light modulators excited at one of subcarrier frequencies is placed in front of the optical demodulator. One of the features of this scheme is the potential immunity from interference among channels.

1 Introduction

To transmit a variety of information and to implement multiple access, subcarrier multiplexed (SCM) optical communication systems are extensively investigated [1].

The main functions of these systems may be summarized as follows. A number of baseband signals are loaded on microwave subcarriers with one to one correspondence. Then the sum of these subcarriers are led to a laser diode or to an external modulator to achieve an intensity modulation of light wave. The transmitted light wave is detected with a demodulator, whose frequency bandwidth is wide enough to include the highest subcarrier frequency. The demodulated subcarriers are then amplified simultaneously, before one of them is extracted using a set of filter and discriminator to reproduce the desired baseband signal.

One of the problems of this system is the interference of channels due to the intermodulation distortion occurring in the course of subcarrier signal processing (simultaneous demodulation and amplification of many subcarriers).

To avoid this intermodulation of subcarriers, an interesting optical prefiltering was recently proposed [2], in which a desired subcarrier is filtered out in the optical range by means of a Fabry-Perot etalon inserted in front of the photo-detector. The light wave containing only one of subcarriers is applied to the photo-diodes, so that there is no cause of interference of channels (subcarriers) in the subsequent amplification process of the signal.

The present paper proposes a more feasible type of de-multiplexing scheme free of intermodulation. This scheme uses a pair of optical modulators excited at one of the subcarrier microwave frequencies, before it is detected with a pair of photo-diodes. In this configuration, the baseband signal included in one of subcarriers is directly detected from the photo-diodes. The detailed performance of this scheme is explained in the order of signal processing.

2 Optical Pre-modulation

Explanation will be made using a branched-waveguide interferometric light modulator utilizing the electro-optic effect of lithium niobate, since this type is most popular. As is widely known, the idealized modulation characteristic of it is expressed by [3]

$$P_o = P_i \left\{ \frac{1}{2} + \frac{1}{2}\sin\left(\pi\frac{v}{V_\pi}\right)\right\} \tag{1}$$

where P_i, v and V_π are the input light-wave power, the modulation voltage applied to the modulator and the half-wave voltage, respectively.

Now, light wave power modulated with N subcarriers is written as

$$P_i = \overline{P}\left\{1 + \sum_{n=1}^{N} C_n \sin(\omega_n t + \phi_n)\right\} \tag{2}$$

where baseband signals are included in amplitude C_n as AM, or in phase ϕ_n as PM or FM. This light wave is fed to the optical modulator excited with a microwave voltage v whose frequency is equal to one of the subcarrier frequencies ω_n

$$v = V_l \cos(\omega_n t + \phi_l) \tag{3}$$

Insertion of Eqs.(2) and (3) into (1) yields

$$P_o = \overline{P}\left\{1 + \sum_{n=1}^{N} C_n \sin(\omega_n t + \phi_n)\right\}$$

$$\cdot\left\{\frac{1}{2}+\sum_{m=1}^{\infty}(-1)^m J_{2m+1}\left(\pi\frac{V_l}{V_\pi}\right)\right.$$
$$\left.\cdot\cos(2m+1)(\omega_n t+\phi_l)\right\} \quad (4)$$

where use was made of the formula

$$\sin(x\cos\theta)=2\sum_{m=0}^{\infty}(-1)^m J_{2m+1}(x)\cos(2m+1)\theta$$

Due to frequency mixing, a number of modulation frequencies appear in the output wave from the modulator [3], [4].

3 Demodulation

This light wave (4) modulated at mixed frequencies is applied to a photo-diode with narrow bandwidth which is sensitive only to frequencies lower than subcarrier microwave frequencies. In Eq.(4) the frequency components lower than the subcarrier's are just

$$P_o=\overline{P}\left\{\frac{1}{2}+\frac{1}{2}C_n J_1\left(\pi\frac{V_l}{V_\pi}\right)\sin(\phi_n-\phi_l)\right\} \quad (5)$$

The output current from the photo-diode is then given by

$$i=\frac{e}{h\nu}\eta P_o\equiv\mathring{\eta}\,P_o$$

where e, $h\nu$ and η stand for electronic charge, energy of a photon and the quantum efficiency of the diode, respectively. The $\mathring{\eta}$ is the conversion factor from the optical power to the current of the photo-detector. The current i contains a term that is proportional to the sine of the phase angle of the subcarrier ϕ_n relative to the phase angle of the local signal ϕ_l. If a signal is included in ϕ_n, this scheme can thus reproduce the signal directly from the light wave, on condition that the local signal voltage (3) is provided. Before explaining how such a local signal voltage is procured, a supplement will be added for the phase demodulation.

Balanced phase demodulation

In the scheme above, DC current due to the light wave carrier flows out of the photo-diode. This DC current can be removed, if we construct an opto-microwave circuit as shown in Fig.1. The light wave $P_{in}=2P_i$ modulated with many subcarriers is divided into two with a branched waveguide and injected into a pair of light modulators each excited with a local signal in reverse polarity. The output light wave from each modulator is injected into each of the photo-diodes. The currents from the pair of diodes are given by

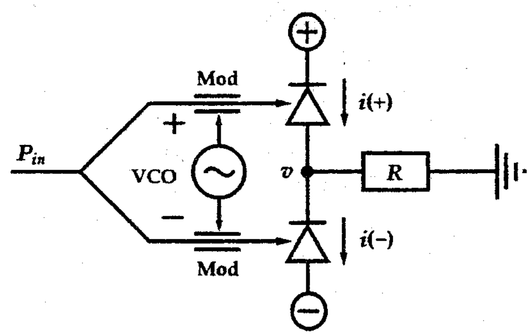

Figure 1: Balanced phase demodulation circuit

$$i(\pm)=\mathring{\eta}\,\overline{P}\left\{\frac{1}{2}\pm\frac{1}{4}C_n L\sin(\phi_n-\phi_l)\right\}$$

where an abbreviation was made as

$$L=2\,J_1(\pi V_l/V_\pi)$$

which measures the modulation factor with the local signal. The sign $\pm$ corresponds to the upper and lower photo-diodes, respectively. As the difference of the currents $i(\pm)$ flows into the load resistance R, the voltage

$$v=V\,\sin(\phi_n-\phi_l) \quad (6)$$

appears at the output terminal of this scheme with DC components being cancelled, where

$$V=(1/2)\,\mathring{\eta}\,\overline{P}C_n LR \quad (7)$$

Eq.(6) states that the output voltage is proportional to the sine of the phase angle of the subcarrier ω_n relative to that of the local signal. In other words, PM or PSK demodulation is directly achievable with this opto-microwave circuit.

Next we consider a method to obtain a local signal.

4 Phase Locked Loop

The output voltage (6) is led to an amplifier $A(s)$ and to a (low-pass) filter $F(s)$ to produce the voltage

$$v_c(t)=v(t)*A(t)*F(t) \quad (8)$$

where $A(t)$ and $F(t)$ are the inverse Laplace transforms of $A(s)$ and $F(s)$, respectively. The symbol $*$ represents the convolution as

$$v(t)*A(t)=\int_0^{\infty}i(\tau)A(t-\tau)d\tau$$

The voltage $v_c(t)$ is applied to a voltage controlled oscillator (VCO), which is used as the local oscillator in Fig.1. The instantaneous oscillation frequency $\omega_n + d\phi_l/dt$ of the VCO is determined in accordance with

$$d\phi_l/dt = Kv_c(t) \quad (9)$$

where K is the frequency sensitivity to the voltage of the VCO.

Inserting Eqs.(8) and (6) into the equation above yields

$$d\phi_l/dt = \Omega(t) * \sin(\phi_n - \phi_l) \quad (10)$$

where

$$\Omega(t) = (1/2) \overset{\circ}{\eta} (t)\overline{P}C_nLR * A(t) * F(t)\ K \quad (11)$$

Introducing the change of variables

$$\phi = \phi_n - \phi_l \quad (12)$$

in Eq.(10), we obtain the fundamental equation for this scheme:

$$d\phi/dt + \Omega(t) * \sin\phi(t) = d\phi_n/dt \quad (13)$$

If this integro-differential equation is solved for $\phi(t)$, the output voltage of the opto-microwave circuit is found from

$$v(t) = V(t) * \sin\phi(t)$$

Subcarrier regeneration

When the circuit above attains the steady state $d\phi/dt = 0$ with ϕ_n = constant, Eqs.(13) and (12) tell that the phase ϕ_l of the local oscillator becomes equal to ϕ_n of the subcarrier.

When $\phi_n \neq$ constant with the frequency characteristic of the loop gain being neglected ($\Omega(s) = \Omega_0$), the frequency deviation $d\phi_n/dt$ of the subcarrier must lie within the limit

$$|d\phi_n/dt| < |\Omega_0|$$

so that Eq.(13) has a real value of $\phi = \phi_n - \phi_l$. In other words, the oscillation frequency of the VCO should be adjusted near ω_n of the subcarrier within the range above. This range can be made arbitrarily wide by increasing the loop gain Ω, as far as the stability condition of $s+\Omega(s) = 0$ from Eq.(15) (next subsection) is satisfied.

Small signal theory

Since Eq.(13) involves nonlinearity, it cannot be solved analytically. When the scheme above behaves well, the phase difference (12) between one of subcarriers and the local signal may be small. In this case, Eq.(13) is linearized, so that it is written in the Laplace transform: $s\phi(s)+\Omega(s)\phi(s) = s\phi_n(s)$, which is solved for $\phi(s)$:

$$\phi(s) = s\phi_n(s)/\{s + \Omega(s)\} \quad (14)$$

as a function of the input signal $\phi_n(s)$. The output voltage of this scheme is then given by

$$v(s) = V(s)\frac{s}{s+\Omega(s)}\phi_n(s) \quad (15)$$

The accuracy of this small signal theory is estimated to be better than $(\sin f)/f \times 100$ %, where $f = (d\phi_n/dt)/\Omega_0$. That is, if the frequency deviation f of the subcarrier relative to the synchronization range Ω_0 is limited less than 1/2, then the maximum error of this small signal theory is −4 %. Otherwise the integro-differential equation (13) must be solved numerically.

5 De-multiplexing Demodulation

FM or FSK demodulation

For SCM systems, frequency modulation or frequency shift keying is normally employed, so that the frequency $d\phi_n/dt$ of a subcarrier is changed with time. This scheme can act as a direct demodulator of an FM or an FSK signal.

In an idealized state where there is no frequency characteristic in the relevant circuits in this scheme, the output voltage through the amplifier is written

$$v_a(s) = V(0)\frac{A}{s+V(0)AFK}s\phi_n(s) \quad (16)$$

where

$$V(s) = \overset{\circ}{\eta} (s)\overline{P}C_nLR/2$$

Eq.(16) tells that this demodulation scheme has a frequency characteristic, even if the relevant circuit has entirely no frequency characteristic. The cut-off frequency V(0)AFK, however, can be made arbitrarily higher by increasing the gain A of the amplifier. As A is increased, the phase-locked characteristic is improved, the difference between the input and the output phases becoming smaller.

If the frequency characteristic of the photo-diodes is taken into account, it is found from the analysis that the time response for an FSK signal is optimized, when the gain of the amplifier is chosen a little less than $\omega_h/V(0)FK$, where ω_h is the cutoff frequency of the photo-diodes. Selection of the filter will bring forth a variety of characteristics of the response of this scheme.

The noise analysis reveals that this scheme senses the quadrature component of noise relative to the phase ϕ_n of an input subcarrier signal, whose magnitude is inversely proportional to the S/N ratio in the input terminal.

PM or PSK demodulation

If the loop gain $\Omega(s)$ of the phase locked loop at DC and low frequency is taken sufficiently higher, then the average value of the phase difference $\phi(s)$ in Eq.(14) between those of the subcarrier and the VCO becomes very small, that is, a local signal having the same phase with the average value (without high frequency components) of the subcarrier is obtained. This local signal can be used to demodulate a PM or a PSK signal in accordance with Eq.(6).

IM or ASK demodulation

If the phase of the local frequency is kept in quadrature with that of a subcarrier, namely $\phi_l = \phi_n - \pi/2$, then IM or ASK signal C_n on a subcarrier is directly demodulated according to Eqs.(6) and (7) with $\sin(\phi_n - \phi_l) = 1$.

Variation

If the non-linearity of the photo-diodes are utilized, the optical pre-modulators can be removed. In this case, the voltage from the VCO is fed to the coupling point v of the diodes, with a filter inserted between v and R to prevent the microwave to leak into the load. As a result of the mixing effect in the diodes [5], the phase detected current will flow into the load R to produce the voltage similar to Eq.(6).

Features of the scheme

The subcarrier homodyne de-multiplexing scheme presented here can directly demodulate the baseband signal from a selected subcarrier without a (subcarrier) filter and a discriminator, so that this scheme is potentially immune from subcarrier interference.

This feature is just compared with that proposed by Greenhalgh et al.[2], in which a Fabry-Perot resonator is used for selection of subcarrier sidebands in the optical frequency range. In their scheme, the frequency of optical source must be highly stabilized as well as the (mechanical) tuning of the F-P resonator. Instead of a large-size F-P resonator, our scheme uses a pair of light modulators excited at a microwave subcarrier frequency, having nothing to do with the optical frequency itself, as is understood from the analysis. Since the subcarrier frequency is several-order lower than the optical carrier's, the tuning is easy by the same order. It should also be noted that this subcarrier homodyne demodulation does not require the high technology as that of an optical homodyne detection.

The scheme proposed by Greenhalgh et al. does not respond to an FM of subcarrier. To realize the SNR merit of FM, they suggest that frequency modulated sub-subcarriers must be employed to amplitude-modulate subcarriers [6]. The present scheme can respond not only to FM, but also to PM or AM (IM).

6 Conclusion

To avoid interference of subcarriers in SCM optical communication systems due to intermodulation distortion in the process of de-multiplexing, a new scheme has been proposed, which performs homodyne demodulation of a selected subcarrier.

The fundamental theory and the analytical results of the performance have been presented together with the explanation of the features of this scheme. The detailed analytical results will be delivered in the Meeting. The numerical analysis has been carried out by M. Konya, a post-graduate student of Kyoto University.

This scheme may be easily realized with components now commercially available in the fields of microwaves and opto-electronics.

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