

OPTICAL COMMUNICATIONS

The present invention relates to a method of generating signals having optical carriers. It finds particular application in the generation of radio frequency (RF) modulations to be carried over optical media.

The principle of modulating an optical beam by an information content is well established, and various methods are known of achieving this. Some arrangements involve controlling the light source (typically a laser) by varying its input bias voltage. Other arrangements use optical devices in the path of the generated beam (typically on an optical fibre) to interrupt the beam. A known optical device for this purpose is the Mach-Zehnder interferometer. The principle of this device is to split the optical beam into two-paths, one or both of which passes through a medium whose refractive index varies as a function of the electrical potential applied to it. By applying an electrical signal to one or both paths, the difference between the path lengths of the two beam paths can be varied, such that the re-combined beams interfere constructively or destructively depending on the electrical fields applied. The intensity of the recombined beam therefore varies in response to the varying electrical input signal.

It is known for the modulation carried by an optical signal to include a carrier frequency in the radio frequency (RF) range. This principle, known as 'Radio by Fibre,' allows a radio signal, including its RF carrier, to be generated at one location and transmitted over the air from another, remote, location. The signal is typically carried by an optical fibre between these locations. This allows the equipment at the point from which the signal is to be transmitted over the air to be kept very simple. In its simplest form it need consist only of a detector to convert the optical input into an electrical signal, and an antenna for transmitting the electrical signal over the air. This is particularly useful in situations where an antenna has to be

located at a point difficult of access, such as a hilltop, because the complex equipment required to generate the radio - frequency carrier in particular the local oscillator can be located at another more accessible location. Moreover, it is possible to achieve economies in a branched network, in which one signal is transmitted to several antenna sites, because only one local oscillator is required to generate the carrier to be transmitted by all the antennas.

The detectors for these arrangements are typically photodetectors. These produce an electrical output which varies with the intensity of incident light. This electrical output therefore corresponds to the modulation, but without the optical carrier frequency.

Known optical systems suffer from a number of practical limitations, in particular in the accurate transmission of high radio frequencies (of the order of a few tens of GHz). As frequencies approach the millimetre waveband (tens of gigahertz) it becomes increasingly difficult to achieve direct modulation of the laser by applying a signal to the input bias voltage, because of inherent physical limitations of the laser devices themselves. Similar constraints apply to modulation devices such as the Mach-Zehnder interferometers discussed above, as the high frequencies necessitate very small dimensions which impose constraints which reduce their efficiency. Velocity matching between the electrical and optical signals also becomes harder to achieve and maintain.

There is an additional problem with the application of signals by means of a Mach-Zehnder optical modulator. As explained above, the principle of these modulators is that as the voltage applied to the electrical input of a Mach-Zehnder interferometer is increased, the difference in optical path length increases. This results in the two optical paths passing in and out of phase, so that the amount of light passing through the interferometer varies as a periodic function of the applied voltage, and not as a linear function. This non-linear response to the input means that

only constant-amplitude signals would be accurately reproduced.

A proposal by O'Reilly and Lane (Electronics letters, Vol 28, No 25, page 2309) addresses the first of these
5 problems. In this proposal, an electrical signal having a frequency ω in the RF band is applied to the control input of an optical modulator. This modulator is biased such that the optical output generated is modulated by a signal dominated by two side bands centred on the optical carrier
10 frequency of the original optical signal fed into the modulator and each spaced from the optical carrier frequency by the frequency of the electrical signal ω . These side bands produce sum and difference beats at an optical receiver such as a photodetector. The 'sum' beat is at twice the
15 optical carrier frequency. The 'difference' beat is at frequency 2ω which is in the RF band. A photoelectric receiver would not be sensitive to the optical-frequency 'sum' beat, but would generate an electrical signal at the 'difference' frequency. This proposal therefore produces an
20 output signal carried by the optical beam which is at twice the frequency of the electrical signal applied to the control input.

O'Reilly and Lane further propose applying an information-containing modulation to this output signal by
25 separating the two side bands using optical filters, modulating one of them with the information content using a second optical modulator, and re-combining them, to generate an output having an optical carrier, modulated by a second, radio frequency, carrier 2ω , and further modulated by the
30 information content. However, this further optical modulation suffers from the non-linearity discussed above, and requires the use of optical filters and a second optical modulator which result in optical losses.

According to a first aspect of the invention there is
35 provided a method of generating a modulated optical signal having a first RF component including a first RF carrier

frequency and an information component, the method comprising the following steps: -

i) Generating a first optical signal having a second RF component including a second RF carrier frequency different
5 from said first RF carrier frequency;

ii) Generating a control signal having a third RF component including a third RF carrier frequency different from said first RF carrier frequency;

said second or said third RF component including the
10 information content;

iii) applying the first optical signal to an optical modulator and

iv) applying the control signal to the optical modulator to modulate the first optical signal so as to produce an
15 output optical signal modulated by said first RF carrier frequency and said information component, said first carrier frequency being said second carrier frequency upconverted by said third carrier frequency or by an integer multiple of said third carrier frequency.

20 The invention has a number of advantages over the prior art. By applying RF components to both inputs of the modulator, an upconversion is achieved. This allows a higher frequency to be generated at the output of the modulator than is applied to either of the inputs. The use of lower RF
25 frequencies in the optical input allows a simpler laser to be used to generate the desired RF signal. The use of lower RF frequencies at the control input of the modulator similarly allows greater flexibility and simplicity in the design of the modulator, which is constrained by the input frequency
30 and not the output frequency.

Either the first optical signal or the control signal may include the information component. The invention also extends to a method of encryption comprising the steps of the first aspect wherein both the input optical signal and the
35 control signal include an information component, one of which is a predetermined encryption code, and to a method of de-encrypting a signal generated in this way, comprising

applying to the output signal a further modulation complementary to that of the predetermined encryption code. This provides a simple way of upconverting and encrypting a signal in one operation.

5 In a preferred embodiment the control signal is an electrical signal, the modulator being of the type where the optical output of the modulator has a non-linear response to the electrical control input. A Mach-Zehnder interferometer is an example of such a modulator. Using a modulator of this
10 type the first RF carrier frequency may simply be a sum of the second and third RF carrier frequencies (i.e the third RF carrier frequency upconverts the second RF carrier frequency to the first RF carrier frequency). However in this type of modulator the amplitude of the control signal may be selected
15 such that the second RF component is upconverted by a frequency which is a desired integer multiple of the third RF component. This allows even larger conversion factors to be created between the control frequency and the output frequency, with consequent lower frequency control signals,
20 further mitigating the design constraints on the modulator.

The modulation carried by the first optical signal is preferably generated by controlling the bias voltage of a laser.

The invention also extends to an optical signal
25 generated according to the method of the invention, and a radio or electrical signal generated by detecting such an optical signal.

According to a second aspect the invention comprises apparatus for generating an optical signal having a first RF
30 component which includes a first RF carrier frequency and an information component, comprising;

- i) an optical modulator having an optical input, an optical output, and a control input;
- ii) means for supplying to the optical input a modulated
35 optical signal having a second RF component including a second RF carrier frequency different from said first RF carrier frequency;

iii) means for supplying to the control input a control signal having a third RF component including a third RF carrier frequency different from said first RF carrier frequency,

- 5 iv) means for applying a modulation comprising said information component to said optical signal or said control input;

the arrangement being such that there is produced at the optical output an optical signal modulated by said first
10 RF carrier frequency and said information component, said first carrier frequency being said second carrier frequency upconverted by said third carrier frequency or by an integer multiple of said third carrier frequency.

In a preferred embodiment the control input is an
15 electrical input and the optical modulator is a Mach-Zehnder interferometer. The means for generating the control signal may be arranged to generate a signal of sufficient amplitude that the second RF component is upconverted by a frequency which is an integer multiple of the third RF component.

20 The means for supplying the optical signal is preferably a laser. Preferably means for controlling the bias voltage of the laser are provided for generating the second RF component.

The input optical signal therefore carries an initial
25 RF modulation, so that the output optical signal comprises an RF modulation which is the initial RF modulation upconverted by the control RF frequency. This allows the use of control frequencies lower than the desired output RF carrier frequency. Moreover, if a modulator having a non-linear
30 transfer function is used, such as a Mach-Zehnder interferometer (whose transfer function is periodic) even larger upconversion factors can be used because by selection of the amplitude of the control signal appropriately, the output can be dominated by a harmonic of the control signal.
35 To understand why this occurs, consider a control signal having a amplitude V_c , causing the difference in path lengths in the optical paths to vary between zero and one wavelength

λ. (See Figure 2). On each cycle of the control signal the path length difference will thus vary from zero to λ and back again. There will thus be two points of constructive interference (at zero and $V_{2\pi}$) and two points of destructive interference (at V_{π}) for each cycle of the control signal, so that the signal applied by the modulator to the optical signal is in this case twice the control signal frequency. By selecting other amplitudes for the control signal different integer multiplication factors can be introduced.

10 In the simple example above the amplitude of the control signal is chosen to vary the path length by a whole number of wavelengths. Varying it over smaller amplitudes can also generate signals having dominant harmonics which may be used in the same way.

15 The invention also extends to an encryption device comprising the elements of the second aspect of the invention wherein means are provided for applying a modulation comprising an encryption code to the optical input or the control input.

20 Information content may be applied to either input signal. In modulators such as Mach-Zehnder interferometers having the non-linearity referred to above, large amplitude modulations of the control input would not be accurately reproduced in the output optical signal. However amplitude modulations applied to the optical input do have a linear response. The Mach-Zehnder interferometer used as the modulator of the preferred arrangement also has a linear response to phase and frequency modulations applied to either the control or the optical input. Combinations, such as

25 phase-amplitude modulation (e.g. quadrature amplitude modulation: QAM) are also possible in the optical input.

According to a third aspect of the invention, there is provided a method of generating an output optical signal having an RF modulation comprising applying an input optical

35 signal to an optical input of a modulator having a non-linear transfer function, applying a control signal having a control RF frequency to a control input of the modulator, the

amplitude of the control signal being such that the output optical signal is modulated by an RF frequency which is an integer multiple of the control RF frequency. The modulator is preferably a Mach-Zehnder interferometer. This aspect of the invention allows high RF frequency modulations to be applied to the optical signal although a lower frequency is applied to the control input. This has the advantages discussed above in mitigating design constraints on the optical modulator.

10 The invention will now be further described by way of example only with reference to the accompanying drawings in which;

Figure 1 is a diagrammatic representation of an arrangement for performing the method of the invention;

15 Figure 2 is a diagram showing the variation of transmissivity of a Mach-Zehnder modulator to changes in applied voltage; and

Figures 3 to 6 are diagrams showing the way in which the frequency multiplication factor changes with the amplitude of the voltage applied to a Mach-Zehnder modulator.

Referring to Figure 1, there is shown an arrangement including a laser 1 having an electrical power input 2, and an optical output 3. A source 4a of an RF electrical signal is connected to the electrical input 2 through amplifier 5. Connected to the optical output 3 of laser 1 is a Mach-Zehnder optical modulator 6. The electrical input 7 of the modulator 6 is fed another RF signal from source 4b through a power amplifier 9. The output 10 of the modulator 6 is connected, through optical fibre 11 to a photodetector 12 which converts the optical signal to an electrical signal. The photodetector is coupled through another amplifier 13 to a radio antenna 14 which converts the electrical signal to a radio signal. The RF electrical signals from either of source 4a or source 4b may include a modulation carrying the required information content. Signal source 4a may generate analogue or digital modulation outputs which may themselves be modulated onto RF carrier frequencies. Signal source 4a

may generate a multichannel output using any suitable modulation scheme such as frequency modulation, amplitude modulation, or phase modulation. Because of the non-linearity of the modulator, source 4b can only supply one
5 channel at a time. This channel may be frequency or phase modulated.

Several ways in which this arrangement may be used will now be described.

In a first method the signal source 4a generates an
10 electrical FM carrier in the gigahertz range suited to the response time of the laser 1. The FM electrical carrier signal carries a modulation in the megahertz band, and provides the input to the laser 1, the optical signal generated by the laser 1 varying directly in response to the
15 electrical input signal to provide a modulated FM optical signal at output 3.

In order to up-convert the optical signal modulated at an intermediate frequency (IF) to a higher frequency the optical signal is mixed in modulator 6 with a local
20 oscillator frequency LO from source 4b. The output of modulator 6 is thus a signal comprising an optical carrier, modulated by a high frequency RF signal being the RF carrier frequency (IF) from source 4a plus the local oscillator frequency of source 4b, itself modulated by the information
25 content. Upconversion therefore takes place within the optical system, and this has a number of advantages over performing it in the electrical systems upstream or downstream of the optical system. In a second arrangement, the information bearing modulation may be applied through
30 signal source 4b. This can be phase or frequency modulated and has an RF carrier frequency.

By supplying the signal from source 4b at a sufficiently large amplitude the RF frequency may be multiplied in the modulator 6 in a manner to be described
35 below, allowing the output of the modulator to be at a higher frequency than the electrical input, thereby avoiding the

problems associated with optical modulators when driven at such high electrical frequencies.

Other arrangements can be devised which are within the scope of this invention. For example, information-bearing signals may be applied by both sources 4a and 4b, that at source 4b being a predetermined code. The two signals will become scrambled in output 10. A remote user, knowing the code signal applied at 4b may receive the scrambled signal over the air from antenna 14, and re-combine the output signal by a signal complementary to that from source 4b, to recover the signal from input 4a.

The use of the modulator as a multiplier of the local oscillator frequency, in addition to its function as a mixer of the local oscillator and optical modulation signals, will now be described.

In figure 2 the horizontal axis shows the voltage applied to the modulator and the vertical axis shows the transmissivity of the modulator. It will be seen that the response of the modulator is highly non-linear with respect to variations in electrical input. It is therefore most suited for provision of a constant amplitude modulation. More complex modulations will be distorted by the non-linear response. In arrangements in which the modulated input 4 is fed to the electrical input 7 of the optical modulator 6, this non-linear response limits use of the system to single channel applications.

In the arrangement according to the present invention, the non-linear response of the modulator can be used to generate harmonics of the local oscillator frequency, thus allowing higher upconversion factors in the modulator.

The output $i(t)$ of the photodetector 12 can be expressed as a sum of its Fourier components I_p :

$$i(t) = \sum_{p=-\infty}^{\infty} I_p \exp(jp\omega t)$$

$$I_p = \frac{1}{\tau} \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} i(t) \exp(-jp\omega t) dt$$

Assume a Mach-Zehnder modulator with a characteristic symmetrical about $V=0$ (Fig. 2), with V_π being the voltage excursion required for the transmissivity of the Mach-Zehnder interferometer to go from full transmission (constructive interference) to full extinction (destructive interference).

Applying a sinusoidal voltage ($V_a \sin \omega t + V_b$) to such an interferometer where:

10 V_a = amplitude of applied voltage
 V_b = d.c bias of applied voltage

gives an output having harmonics whose Fourier amplitudes are then given by:

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$$I_p = \frac{1}{2} \left(1 + \cos \left(\frac{\pi V_b}{V_\pi} \right) J_0 \left(\frac{\pi V_a}{V_\pi} \right) \right), p = 0$$

$$\frac{1}{2} \cos \left(\frac{\pi V_b}{V_\pi} \right) J_p \left(\frac{\pi V_a}{V_\pi} \right), p \text{ even}, \neq 0$$

$$\frac{1}{2} \sin \left(\frac{\pi V_b}{V_\pi} \right) J_p \left(\frac{\pi V_a}{V_\pi} \right), p \text{ odd}$$

20 By selecting the bias voltage to be $\frac{1}{2}(V_\pi)$ we can generate even-only harmonics. By selecting the bias voltage to be V_0 we can select odd-only harmonics. Selecting $V_b = 0$ reproduces the Mach-Zehnder transfer function in the zeroth

harmonic as the bias voltage V_b is tuned, and zero for the higher harmonics.

The d.c amplitude is equal to $|I_0|$. (ie the mean light power transmitted through the modulator)

5 The a.c amplitude is equal to $|2I_p|$, $p > 1$.

Thus we can define the modulation depth for the "p' th" harmonic as:

$$M_p = \left| \frac{2I_p}{I_0} \right|$$

10 However the value of I_0 changes with applied a.c. modulation voltage V_a (as well as with bias voltage V_b). Therefore, maximising the modulation depth does not necessarily correspond to maximising the amplitude of a particular harmonic.

15 It is perhaps more convenient to choose the d.c. level when $V_a = V_b = 0$ as the reference, in which case $I_0 (V_a = V_b = 0) = 1$.

Then our modified modulation depth becomes:

$$M_p = \left| \frac{2 I_p(V_a, V_b)}{I_0 (V_a = V_b = 0)} \right|$$

$$= \cos \left(\frac{\pi V_b}{V_\pi} \right) J_p \left(\frac{\pi V_a}{V_\pi} \right), \quad \begin{matrix} p \text{ even} \\ p > 1 \end{matrix}$$

20

$$\sin \left(\frac{\pi V_b}{V_\pi} \right) J_p \left(\frac{\pi V_a}{V_\pi} \right), \quad \begin{matrix} p \text{ odd} \\ p > 1 \end{matrix}$$

Figures 3 to 6 show transfer characteristics calculated for various values of V_a and V_b . Odd harmonics are biased at $\frac{1}{2}V_a$, even ones are biased at $V=0$. In these 5 figures the input voltage is shown as a dotted line and the output as a solid line. The voltages applied (arbitrary units) are given in the Table below: -

Figure	V_a	V_b	Principal Harmonic
3	1	$\frac{1}{2}V_a$	Fundamental
4	59	0	2nd Order
5	112	$\frac{1}{2}V_a$	3rd Order
6	877	0	10th Order

In this way, by applying different amplitudes V_a to the 15 electrical input, modulations of different frequencies can be produced in the optical system.

As will be seen, the output wave form is not the same shape as the input. It can therefore be seen from these Figures that multiple-channel signals applied to such a 20 modulator input would be distorted and thus difficult to extract at the receiver. However, for a single-frequency input such as a local oscillator this is not important as unwanted harmonics can be filtered out downstream.

In the simple case described with reference to Figures 25 3 to 6 the optical input is unmodulated, so that the optical output is modulated only by the multiplied control frequency. However, if the optical input signal already carries a modulation, the optical modulator will mix this modulation with the multiplied control frequency to provide an 30 upconversion.

EXAMPLE

In the exemplary embodiment of Figure 1, the signal source (4a) was embodied by an Avantek VTO 9090 oscillator 35 generating channels between 950-1750 MHz. The output from

this was used to modulate a Lasertron QLXS 1300 MW laser (1), whose output was directed along a step-index single mode 9/125 μm optical fibre (3) to a BT&D IOC 2000-1300 modulator (6). The control input (7) to this modulator was supplied by a Marconi 2042 local oscillator (4b) working at 3.4 GHz and amplified by a Minicircuits ZFL/42 amplifier (9) such that the eighth harmonic of the local oscillator frequency (ie 27.2 GHz) dominated the signal response. The output of modulator 6 thus had a RF carrier frequency of 27.2 GHz + (950 to 1750 MHz) or 37.15 to 37.95 GHz, which was fed through another step-index single mode 9/125 μm optical fibre 11 to a detector (12) such as described in Wake D: "A 1550nm Millimetre - wave Photodetector with a Bandwidth Efficiency Product of 2.4 THz". (Journal of Lightwave Technology, 1992, Vol 10 pages 908-912). The output from this detector was amplified by a Celeritek CSA946892 amplifier (13) and transmitted from a standard gain 20dBi horn antenna as a microwave transmission in the 37GHz band.

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While the embodiments described above have all included Mach-Zehnder interferometers, those skilled in the art will appreciate that the configuration of the interferometer is not significant; any type of interferometer which exhibits non-linear transmission characteristics such as electro-absorption modulators may be used instead. All that is required is that it should exhibit an appropriate transmission characteristic.

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CLAIMS

1. A method of generating an optical signal having a first RF component including a first RF carrier frequency and an information component, the method comprising the following steps: -
 - i) generating a first optical signal having a second RF component including a second RF carrier frequency different from said first RF carrier frequency;
 - 10 ii) generating a control signal having a third RF component including a third RF carrier frequency different from said first RF carrier frequency;
said second or said third RF component including the information content;
 - 15 iii) applying the first optical signal to an optical modulator and
 - iv) applying the control signal to the optical modulator to modulate the first optical signal so as to produce an output optical signal modulated by said first RF carrier frequency and said information component, said first carrier frequency being said second carrier frequency upconverted by said third carrier frequency or by an integer multiple of said third carrier frequency.
- 25 2. A method according to claim 1, wherein the first optical signal includes the information component.
3. A method according to claim 1, wherein the control signal includes the information component.
- 30 4. A method according to claim 1, being a method of encryption, wherein both the input optical signal and the control signal include an information component, one of which is a predetermined encryption code.
- 35 5. A method according to any preceding claim, wherein the control signal is an electrical signal.



6. A method according to any preceding claim, wherein the optical output of the modulator has a non-linear response to the control signal.

5 7. A method according to claim 6, wherein the amplitude of the control signal is selected such that the second RF carrier frequency is upconverted to the first RF carrier frequency by a frequency which is an integer multiple of the third RF frequency.

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8. A method according to any preceding claim, wherein the first optical signal is generated by controlling the bias voltage of a laser.

15 9. A modulated optical signal having a first RF component including a first RF carrier frequency and an information component, when generated by the method of any preceding claim.

20 10. An electrical or radio signal having a first RF carrier frequency and an information component, generated by detecting an optical signal modulated by an RF component comprising a first RF carrier frequency and the information component, the optical signal being generated by the method
25 of any of claims 1 to 8.

11. A method of de-encrypting a signal according to claim 9 or claim 10 when generated according to the method of claim 4 or any claim dependent thereon, comprising applying to the
30 signal a further modulation complementary to that of the predetermined encryption code.

12. Apparatus for generating an optical signal having a first RF component, which includes a first RF carrier
35 frequency and an information component, comprising
i) an optical modulator having an optical input, an optical output, and a control input;



- ii) means for supplying to the optical input a modulated optical signal having a second RF component including a second RF carrier frequency different from said first RF carrier frequency;
- 5 iii) means for supplying to the control input a control signal having a third RF component including a third RF carrier frequency different from said first RF carrier frequency,
- iv) means for applying a modulation comprising said
10 information component to said optical signal or said control input;

the arrangement being such that there is produced at the optical output an optical signal modulated by said first RF carrier frequency and said information component, said
15 first carrier frequency being said second carrier frequency upconverted by said third carrier frequency or by an integer multiple of said third carrier frequency.

13. An encryption device comprising apparatus according to
20 claim 11, further comprising means for applying modulation comprising information components to both the optical signal and the control signal, one of the information components being a predetermined encryption code.

25 14. Apparatus according to claim 12 to 13 wherein the control input is an electrical input.

15. Apparatus according to claim 14, wherein the optical modulator is a Mach-Zehnder interferometer.

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16. Apparatus according to claim 15, wherein the means for supplying the control signal is arranged to generate a signal such that the second RF component is upconverted by a frequency which is an integer multiple of the third RF
35 component to generate the first RF component.



17. Apparatus according to any of claims 12 to 16, wherein the means for supplying the modulated optical signal comprises a laser and means for controlling the bias voltage of the laser for generating the second RF component.

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18. A method of generating an output optical signal having an RF modulation comprising applying an input optical signal to an optical input of a modulator having a non-linear transfer function, applying a control signal having a control
10 RF frequency to a control input of the modulator, the amplitude of the control signal being such that the output optical signal is modulated by an RF frequency which is an integer multiple of the control RF frequency.

15 19. A method according to claim 18, wherein the modulator is a Mach-Zehnder interferometer.

20. A method according to claim 18 or claim 19, wherein the input optical signal carries an initial RF modulation,
20 the output optical signal comprising an RF modulation which is the initial RF modulation upconverted by an integer multiple of the control RF frequency.