MICROWAVE OPTO-ELECTRONICS

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ABSTRACT
The low-loss, wide bandwidth capability of optical fibre transmission systems makes them attractive for the distribution and processing of microwave signals. This paper will review the techniques used for generating, transmitting and detecting microwave modulated optical signals and will describe typical systems applications.

1. INTRODUCTION
Digital optical fibre systems now carry the bulk of terrestrial long distance communications traffic and work is under way to bring fibre into the local network. The wideband transmission properties of fibre also suggest applications in the transmission and processing of microwave signals, and it is these applications that form the focus of this paper.

After a brief review of the properties of the optical fibre transmission medium, technologies for the generation, transmission and detection of microwave modulated optical signals are described. The concept of direct control of microwave devices using optical signals is introduced, with examples of the major signal processing functions realised so far.

Applications of these technologies to microwave systems are then described, including wideband transmission links for cable television distribution and antenna remoting, delay line signal processing and phased array signal distribution and beam forming.

2. FIBRE TRANSMISSION OF MICROWAVE SIGNALS
Interest in the use of optical techniques for wideband signal transmission arises directly from the low transmission loss possible in optical fibre compared with electrical media. Figure 1 shows the loss performance, as a function of signal frequency, for a 9.5mm rigid coaxial system, an X-Band rectangular waveguide (WG-16) and silica optical fibre at wavelengths of 850nm and 1.550nm.

It can be seen that the loss figures for optical fibre at microwave signal frequencies are much lower than for the metallic media. The rise in fibre loss at high signal frequencies is due to dispersion - a non-line narrowed semiconductor laser of linewidth 0.2nm was assumed for the comparison.

In order to take advantage of the low loss transmission property of optical fibre it is necessary to convert the signal from the electrical to the optical domain before transmission and return it to the electrical domain after transmission. The simplest approach is to modulate the intensity of the optical source and detect the modulation at the receiver using a wide bandwidth photodiode.

2.1 Sources
For intensity modulation schemes the only suitable directly modulated source is the semiconductor laser, and bandwidths in excess of 30GHz have been demonstrated [1]. Turning now to external modulators, Mach-Zehnder interferometric modulators [2] have been realised in both lithium niobate [3] and III-V semiconductor technologies [4] with bandwidths exceeding 50 GHz.

For links involving transmission distances of more than 1km, where fibre dispersion effects can become significant, it is important to minimise the spectrum occupancy of the modulated optical signal. External modulators used with narrow linewidth sources, such as laser diode pumped YAG lasers, can offer a significant advantage over directly modulated semiconductor lasers for such applications.
2.2 Transmission
In order to avoid the modal noise problems characteristic of multi-mode fibre systems, single mode fibre is used in most microwave opto-electronic systems. Table 1 gives loss and dispersion values for silica fibre at the three most used transmission wavelengths. For short distance applications, such as optical signal distribution in phased array antennas, loss and dispersion do not present a serious limitation, even at 850nm wavelength, but for longer distance applications, such as antenna remoting or delay line signal processors 1,300nm or 1,550nm wavelength operation is preferred. The availability of narrow linewidth, high power laser diode pumped Nd:YAG lasers for 1,300 nm wavelength has made this the wavelength of choice for many current systems. Future systems are expected to move to 1,550nm, as narrow linewidth sources become more widely available since dispersion shifted fibre with dispersion less than 1.5ps/km/nm for a loss penalty of 0.1dB/km can be produced for this wavelength and high performance optical fibre amplifiers are available.

Optical amplifiers enable 'transparent' optical systems to be realised, in which signals of near arbitrary format can be distributed with small degradation due to noise and amplifier non-linearity. The most important technologies for amplifiers are the travelling wave semiconductor amplifier (SLA) [5] and the doped fibre amplifier (DFA) [6]. Since the fluorescence lifetime of rare earth lasing ions such as erbium is long (>10ns) low distortion performance can be maintained in DFAs for modulation frequencies down to the kHz region, whereas in SLAs significant distortion is observed for modulation frequencies below 1 GHz [5].

The choice between SLAs and DFAs for microwave opto-electronic applications depends on the systems context. SLAs can be integrated into opto-electronic integrated circuits (OEICs) whereas DFAs interface naturally with fibre systems. SLAs offer greater power-added efficiency, an important requirement for space applications, whereas DFAs offer lower added noise and lower minimum modulation frequency. It therefore seems likely that both types will find applications.

Where multiway signal distribution is required, complex assemblies of fused, tapered couplers, with excess losses of less than 0.2dB per bifurcation, have been realised [7].

2.3 Detection
For wideband links depletion layer photodetectors are preferred and 3dB bandwidths in excess of 100 GHz have been reported [8]. Two-terminal edge-coupled heterostructure bipolar transistor detectors having unity current gain frequencies exceeding 30 GHz have also been reported [9] and offer the attraction of an internal gain mechanism.

2.4 Noise Performance
For an intensity modulation/direct detection (IMDD) system there are four major sources of noise: source intensity noise, including contributions from Johnson noise in the laser matching circuit; amplifier noise, if optical amplifiers are used; shot noise due to the flow of current in the photodetector and Johnson noise in the photodetector and its load resistance. For small values of loss the limitation is usually laser intensity noise or shot noise. For large loss values Johnson noise in the detector and load is dominant. The situation when optical amplifiers are included depends on the location of the amplifier within the transmission system. By placing the amplifier immediately before the detector the significance of detector and subsequent amplifier noise can be reduced and a system penalty only slightly greater than 3 dB above the shot noise limit obtained. With currently available technology microwave opto-electronic links with signal to noise ratios better than 150dB.Hz can be realised.

2.5 Other Modulation Modes
Whilst most currently deployed transmission systems use intensity modulation, the wideband capability of fibre transmission makes other modulation modes of interest. Coherent systems, in which the received signal is mixed with an optical local oscillator prior to detection have been reported for intensity, frequency and phase modulation. If the source is intensity modulated and heterodyne detection is used the output is proportional to the square root of the received optical power so that a square law detector must be used to provide overall system linearity. Fong et al.[10] have demonstrated this approach using semiconductor laser sources. The system has the attraction that the main linewidth penalty arises from heterodyned source power falling outside the IF bandwidth. Thus by using a wide IF filter bandwidth and a post-detection filter the system can be made relatively insensitive to source linewidth and drift in source and local oscillator laser frequencies, allowing commercially available
semiconductor lasers with linewidths of > 10 MHz to be used. The system offers the advantage of improved receiver sensitivity through coherent detection and thus is useful at wavelengths where good optical pre-amplifiers are not available. System linearity is limited by the linearity of the source intensity modulation characteristic and by the accuracy of the square law detector characteristic. It therefore can be no better than for an IMDD system.

In an amplitude modulation system the peak electric field produced by the source is linearly proportional to the modulating signal. Thus the source power is proportional to the square of the modulating signal. An heterodyne receiver followed by envelope detection would give an output linearly proportional to the modulating signal. Thus a square law detector is not required. Unfortunately, directly modulated semiconductor lasers have a near linear intensity modulation characteristic, whilst interferometric external modulators have a raised sine intensity modulation characteristic. A convenient linear amplitude modulator is therefore not available.

Frequency modulation is extensively used in radio communication systems, because it enables modulated signal bandwidth to be traded for improved receive signal to noise ratio. Similar advantages are available in the optical domain and are attractive since the available transmission bandwidth is large. The main practical difficulty has been to obtain an optical source capable of uniform FM response up to microwave frequencies. However, this problem has now largely been overcome by the development of the reverse bias quantum well laser tuning technique [11]. The fundamental limitation to signal to noise ratio in an optical FM (OFM) system arises from the finite laser linewidth and values below 100 kHz are required to give signal to noise ratios above 140 dBHz for peak frequency deviations of a few GHz [12]. However, the high sensitivity of the coherent receiver and the post-detection signal to noise ratio enhancement inherent with FM enable low power sources to be used thus helping to overcome stimulated Brillouin scattering limits in long links.

Phase modulation places stringent requirements on optical source linewidth. For this reason phase modulation analogue transmision systems have received relatively little attention. A method of overcoming the phase noise sensitivity by using a common laser in an heterodyne arrangement has been studied by Kalman and Kazovsky [13]. However, since this requires the local oscillator signal to be transmitted with the signal it would be difficult to apply to long links.

3. OPTICAL CONTROL OF MICROWAVE DEVICES

In the systems described in the previous section the optical signal was returned to the electrical domain using a depletion photo-detector. An alternative approach is to use the optical signal to control or introduce signals directly into microwave devices. This approach has several attractions. First, no extra electronic circuits are required to process the detected signals before application to the microwave device; nor are any circuit parasitics, which may limit response speed, introduced. Second, optical control introduces an extra control port to the microwave device. Third, the optical control signal is immune to most electromagnetic disturbances, such as EMP.

The basic process used in direct optical control of microwave devices is photo-generation of carriers within the device by the incident optical signal, usually through intrinsic absorption. In depletion regions this produces a photocurrent and alters the built-in potential thus changing the device capacitance. In undepleted material the photoconductive effect increases the conductivity of the semiconductor material.

Optical control of a wide range of microwave devices has been demonstrated [14]; some of the more important examples are described below.

3.1 Optical control of amplifiers

The gain of microwave MESFETs and HEMTs depends strongly on the gate-source bias. It is possible to control the gain of amplifiers using these devices by illuminating the gate region and including an appropriate series resistor in the gate bias circuit to produce a change in gate bias in response to the optically generated current [15]. Gain changes of up to 20dB in MESFET amplifiers can be achieved using optical powers of a few microwatts.

3.2 Optical control of oscillators

Three main forms of oscillator control are possible. In optical switching a change in the intensity of the optical control signal changes the oscillator output power. In optical tuning the optical control signal intensity is also
varied, but the intensities used are smaller and give a change in oscillator frequency without significant oscillator output power variation. Finally, in optical injection locking the optical control signal is intensity modulated at a frequency close to the free-running frequency of the oscillator \( (k=1, \text{ fundamental locking}) \), one of its harmonics \( (k \text{ integral, harmonic locking}) \), or one of its subharmonics \( (k \text{ fractional, subharmonic locking}) \). The modulated optical signal absorbed in the device active region gives rise to current flow at the modulation frequency in the device, leading to injection locking of the oscillator output frequency.

The above phenomena have been demonstrated for oscillators using IMPATT diodes [16], MESFETs [17] and bipolar transistors [18]. The tuning and injection locking ranges have generally been less than 1% of oscillator free-running frequency owing to difficulty in coupling light into the active region of the device efficiently. Recent work on HBTs [19] indicates that they offer good prospects for overcoming this difficulty.

3.3 Optically pumped mixers and phase detectors

In an optically pumped mixer the signal input to the device is electrical but the local oscillator source is supplied by an intensity modulated optical source. The reverse arrangement in which an electrical local oscillator signal is used to down-convert an intensity modulated optical signal has also been demonstrated [20]. Integrating the photodetection and mixing functions offers the attraction that electrical coupling at the local oscillator frequency between a separate detector and mixer with consequent matching and parasitic component problems, is not required. There is also the attraction of simplicity. Photoconductive mixers fabricated in GaAs have been realised for frequencies up to 4.5GHz [21], but the optical power requirements are in excess of 10mW for efficient operation. Tunnelling in reverse biased Schottky diodes has been used to give a mixer with a conversion loss of less than 16dB [22], with lower losses predicted for more efficient optical coupling. Optically pumped mixers have also been realised using MESFETs [23] and HEMTs [24].

A more recent development has been a phase detector using MESFETs which produces an electrical output representing the phase difference between two intensity modulated optical inputs [25].

4. MICROWAVE SYSTEMS APPLICATIONS

4.1 Signal distribution and processing

The wideband signal transmission properties of optical fibre make it possible to transmit a group of microwave frequency division multiplex (FDM) channels from an antenna to a remote site without prior de-multiplexing [26].

The cable television industry is also using wideband fibre technology for signal distribution. Figure 2 shows the microwave sub-carrier multiplexing technique used. Each channel is mixed with a sub-carrier in the electrical domain to form a composite signal which is used to modulate the optical source. Linearity requirements in such systems are stringent and are the subject of intensive study [27]. Similar techniques have been proposed for signal distribution in cellular radio systems [28].

Optical fibre delay lines offer longer delays for microwave bandwidth signals than competing technologies, such as bulk acoustic wave devices. Deborgies et al [29] report a 100μs optical fibre delay line with a directly modulated semiconductor laser source, for use up to 8GHz. Signal to noise ratio exceeds 127dB.Hz up to 4GHz, falling to 115dB.Hz at 8GHz. Higher figures would be achievable using an externally modulated source. However, the existing system exceeded the performance of bulk acoustic wave technology for all frequencies greater than 1GHz.

4.2 Phased array antennas

In a phased array antenna the beam is formed by adjusting the phase relationship between a number of radiating elements. Advances in monolithic microwave integrated circuits (MMIC) make it possible to use active elements at acceptable cost. Much of the expense then lies in the signal distribution scheme required to obtain the necessary phase relationship between elements. Traditional microwave power splitters and transmission systems are cumbersome, lossy and difficult to apply to conformal antennas, particularly at millimetre-wave frequencies. There has thus been interest in optical fibre techniques for both signal transmission and, more recently, for beam forming [30].
Birmayer and Wale [31] have successfully demonstrated the use of integrated optics coherent techniques for beam forming. Figure 3 illustrates the principle. Two optical signals are generated with a frequency difference equal to the desired microwave frequency. One of the signals passes through an optical phase shifter, experiencing a phase shift, $\phi$. The two signals are then combined and illuminate a photodiode. The output signal from the photodiode includes a component at the difference frequency, with phase $\phi$. Thus the optical phase shift is translated to the microwave output. Crucial to the success of such techniques is the availability of a suitable technology for generating the required optical frequencies. Optical phase lock loops (OPLL) using laser diode pumped YAG lasers have been used in systems demonstrators. Work on wideband OPLL using semiconductor lasers [32] suggests that this will be a viable approach for future systems.

5. CONCLUSION

The application of opto-electronic techniques in microwave systems depends on advances in wideband opto-electronic technology. Directly modulated sources, external modulators and detectors, with bandwidths extending into the millimetre-wave region, are now commercially available. The use of external modulators with high power, low intensity noise sources enables optical links with excellent noise performance to be realised, the main limit on this approach being stimulated Brillouin scattering in long fibre transmission paths. Optical amplifier technology enables wideband networks with well controlled noise performance to be constructed, and seems likely to play an important part in distribution networks for phased array antennas and cable television. Advances in coherent optical signal generation and processing technology suggest that it will play an increasing part in optical beam forming and signal processing schemes.

An issue that is becoming of increasing importance, as noise limitations in microwave opto-electronic systems are overcome, is the problem of non-linearity in optical modulation schemes. The inherent sinusoidal non-linearity of interferometric optical modulators is one example of this. A number of groups are working on techniques for linearising microwave opto-electronic components using electrical pre-distortion or feed-forward/feedback techniques.

The application of optically controlled microwave devices in systems has been hampered by difficulties in achieving efficient coupling of the incident light to the device without compromising microwave performance. Recent advances in microwave HBTs suggest that their development as optically controlled devices will overcome this limitation.

A number of the applications proposed for microwave opto-electronics when the technology was in an embryonic state, such as antenna remoting and cable television distribution have now become commercial realities. With continued investment in the underlying technology many more applications will also come to fruition.

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REFERENCES


Figure 1 - Comparison between signal transmission loss of optical fibre and metallic transmission media.

\[ E_0 = E_0 \sin(\omega_0 t) \]

\[ E_1 = E_1 \sin(\omega_1 t) \]

Figure 2 - Microwave sub-carrier multiplexing technique.

\[ E'_1 = \hat{E}_1 \sin(\omega_1 t + \phi) \]

Figure 3 - Coherent optical beam former-operating principle.

<table>
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<tr>
<th>Wavelength (nm)</th>
<th>Loss (dB/km)</th>
<th>Dispersion (ps/km/nm)</th>
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<tbody>
<tr>
<td>850</td>
<td>2.0</td>
<td>90</td>
</tr>
<tr>
<td>1,300</td>
<td>0.4</td>
<td>&lt;4</td>
</tr>
<tr>
<td>1,550</td>
<td>0.2</td>
<td>&lt;17</td>
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Table 1 - Loss and dispersion of silica optical fibre.