configuration of Fig. 3 in parallel, with one path generating $v_{in}(n)$, while the other $-v_{in}(n)$. These two signals are then sampled alternately to form the final output $v_{out}(n)$. Note that the two op-amps may have different offset voltages, and $v_{out}(n)$ will still be offset-free.

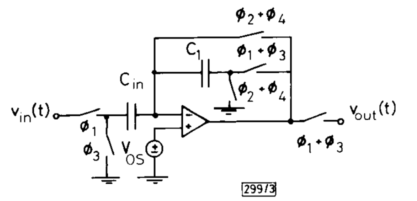

Fig. 3 *Four-phase offset-free modulator*

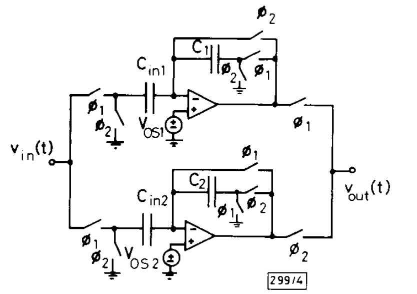

Fig. 4 *Two-phase offset-free modulator*

Experimental results: The four modulator circuits have been built using hardwired discrete components: μA741 op-amps, CD4016 analogue switches, and ±10% accurate 1·5 nF ceramic capacitors. The carrier signal was a 10 kHz, ±2·5 V square wave, while the input signal was a 500 Hz sinusoid with a peak amplitude of 2·0 V. Fig. 5*a* shows the input voltage of the two-phase offset-free modulator of Fig. 4, while Fig. 5*b* shows its spectrum. For the experiment, artificially high input offset voltages of +1·0 and −1·0 V were generated externally for the two op-amps, to demonstrate the offset-free property of the circuit. These offset voltages did not appear in $v_{out}(t)$. The observed spectrum agreed well with the theoretical predictions based on eqn. 2.

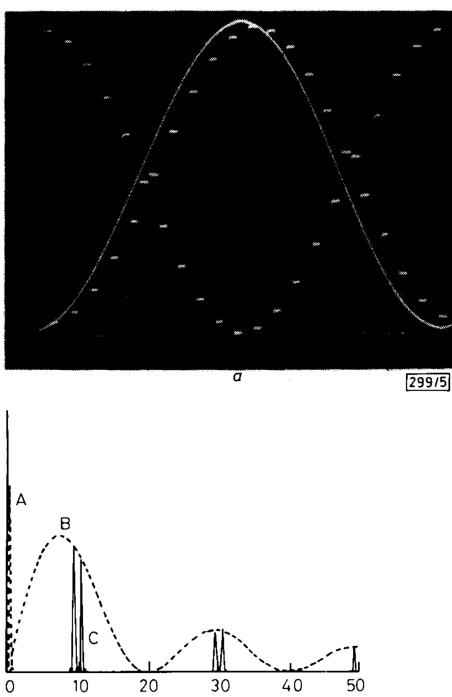

Fig. 5

a Output signal of two-phase offset-free modulator (*x*-axis: 0·2 ms/div, *y*-axis: 0·5 V/div)

b Output spectrum of two-phase offset-free modulator (A: input spectrum, B: envelope function $|\text{sinc}\,(\omega T/4)\,\sin\,(\omega T/4)|$, C: measured output spectrum)

Conclusions: Four novel SC modulator circuits were described. Experimental results showed that the new circuits can provide effective modulation and operate at high speed.

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EXPERIMENTAL DEMONSTRATION OF MULTIWAVELENGTH OPTICAL NETWORK WITH MICROWAVE SUBCARRIERS

Indexing terms: Optical communications, Acousto-optics, Optical filters, Multiplexing

We use the unique multiwavelength filtering capability of the acousto-optic tunable filter to demonstrate multiple broadband services with only one fixed-wavelength transmitter and receiver per user in the first experimental demonstration of a multiwavelength subcarrier network.

Introduction: We use the unique multiwavelength filtering capability of the acousto-optic tunable filter[1] to demonstrate multiple broadband services with only one fixed-wavelength transmitter and receiver per user in the first experimental demonstration of a multiwavelength[2] subcarrier network.[3–5] In particular, we achieve broad wavelength utilisation (1·3–1·56 μm by wavelength-division multiplexing), narrow channel spacing (100 MHz by subcarrier multiplexing), variable-rate transmission (560 Mbit/s baseband and 50 Mbit/s FSK), and simultaneous delivery of multiple services to and from different nodes using only one optical transmitter and receiver per subscriber node. Both point-to-point and broadcast services are supported.

An essential feature is the ability of the network to perform wavelength selection at the receiving end. Without this, the network would be no different from other wavelength-independent, broadcast-star subcarrier networks (e.g. Reference 3) in which the entire usable bandwidth is limited to only a few GHz in the microwave domain. We use an acousto-optic tunable filter (AOTF)[6,7] to accomplish wavelength selection. The unique advantage of the AOTF over other kinds of optical tunable filters is that multiple nonadjacent optical wavelengths can be selected simultaneously,[1] making multiple services to and from different subscribers possible. The AOTF is also electronically tunable, with an extremely broad tuning range (1·3–1·56 μm),[7] and a moderately narrow passband (10 Å FWHM).[1] After photodetection, microwave tunable filters are used to separate various microwave subcarrier (MSC) channels from all selected optical wavelengths.

Experimental set-up: The experimental set-up is shown in Fig. 1. Four DFB lasers were used as transmitters. One laser

(1·528 μm) was modulated by a composite RF signal that consists of a 560 Mbit/s pseudorandom (PR) NRZ baseband signal combined with a 50 Mbit/s PR frequency-shift keyed

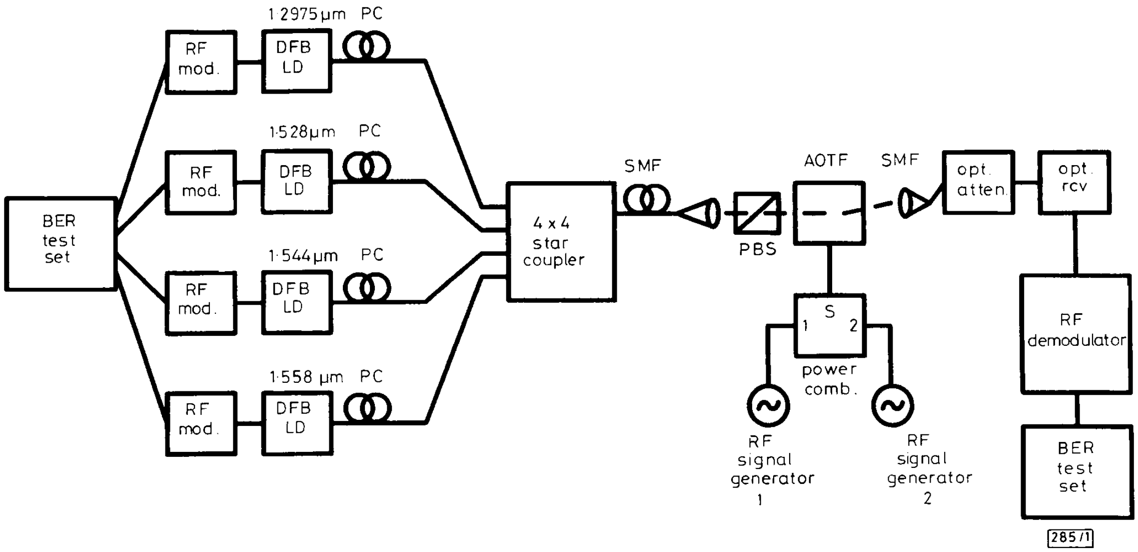

Fig. 1 *Experimental set-up*

(FSK) MSC signal centred at 1·1 GHz, while the other three lasers were modulated individually by 50 Mbit/s PR FSK MSC signals centred at 1·1, 1·2 and 1·3 GHz, respectively. The optical modulation index of each MSC FSK channel was about 50%, and the total frequency deviation was about 50 MHz.

The modulated laser signals were polarisation-controlled and combined by a 4 × 4 single-mode broadband (1·3–1·6 μm) star coupler. The output beam was collimated, passed through a polarising beam splitter (PBS) and then through a bulk-wave AOTF[7] that was driven by two RF frequencies to select two wavelengths simultaneously and independently.[1] The RF frequencies used to select the optical wavelengths in the 1·3–1·56 μm region ranged from 65 to 80 MHz. Each wavelength was selected by 1·5 W of RF power, so that the resulting diffraction efficiency was about 20% per wavelength. Since the transducer of the AOTF could only tolerate ~3 W of RF power, we could only select two wavelengths at a time. More wavelengths could have been selected by using lower RF drive power per wavelength, thereby sacrificing the diffraction efficiency. The total fibre-to-fibre insertion loss of the AOTF was about 10 dB. The optical signal was detected by a custom-designed *pin*FET receiver optimised for baseband 1 Gbit/s transmission rate. RF filters were then used to separate the 560 Mbit/s baseband signal and the MSC signals for demodulation.

Measurements: Fig. 2 shows the measured BER against received optical power plots for the 1·544 μm, 50 Mbit/s MSC channel (curve *f*) as well as the 1·528 μm baseband channel at various bit rates (curves *a*, *b* and *c*). For the 1·528 μm channel, with the normally accompanying MSC channel turned off, the extinction-ratio power penalty incurred on the 560 Mbit/s baseband was about 5·6 dB (curve *d*). When the 50 Mbit/s FSK modulation at 1·1 GHz was added to the baseband, the baseband signal suffered an extra 0·5 dB power penalty owing to intermodulation distortion from the laser. When all the other transmitters (1·298, 1·544, and 1·558 μm) were turned on, any additional penalty owing to optical crosstalk was negligible ($\leq 0{\cdot}2$ dB).

The above measurements were made for single wavelength (1·528 μm) selection by the AOTF. When a second wavelength (1·544 μm) carrying a single FSK signal at 1·2 GHz was also selected by the AOTF, the 1·528 μm wavelength channels suffered about 2·2 dB power penalty (curve *e*). The corresponding effect of the 1·528 μm wavelength signals on the 1·544 μm MSC channel was about 1·2 dB (curve *g*). The difference in the power penalties originated from the asymmetry of the AOTF sidelobe response characteristics. These penalties were solely due to the presence of the second RF control signal in the AOTF, which we verified by turning off the 1·544 μm laser

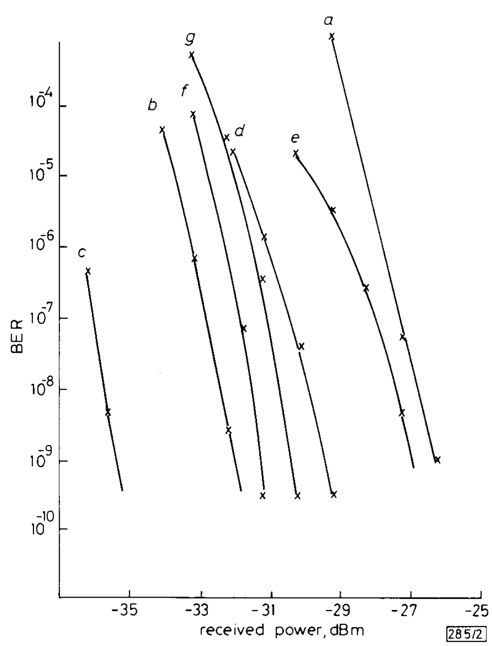

Fig. 2 *Receiver sensitivities and BER curves*

a 1·4 Gbit/s (no extinction penalty)
b 1·0 Gbit/s (no extinction penalty)
c 560 Mbit/s (no extinction penalty)
d 560 Mbit/s, biased at 40 mA (extinction penalty ~5·6 dB)
e 560 Mbit/s, biased at 40 mA, with RF interference
f FSK receiver sensitivity at 50 Mbit/s (no RF interference)
g FSK receiver sensitivity at 50 Mbit/s (with RF interference)

while keeping the second RF in the AOTF. We noticed little change in the BER. The penalty depended on the acousto-optic crosstalk level, and was a result of acousto-optic interaction of the two RF signals with the optical wavelength in the AOTF; the two RF components caused different acousto-optic frequency shifts, resulting in heterodyne mixing when they beat together in a square-law detector. When the acousto-optic crosstalk level was low, as was true for the 1·3 and 1·526 μm channels, this penalty was undetectable. Further discussion of this effect and its implications for system design will be presented elsewhere.[8]

Conclusions: We have demonstrated a multiwavelength network that uses microwave subcarriers for multiple services transmission and distribution. Using an AOTF, we have achieved broad multiple-wavelength selection for the first time to support multiple services in a local distribution network. Both 560 Mbit/s baseband NRZ digital data and 50 Mbit/s FSK digital data at 1·1–1·4 GHz were successfully transmitted and received with a BER better than 10^{-9}.

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POWER PENALTY ANALYSIS DUE TO POLARISATION DIVERSITY ON 1·2 Gbit/s OPTICAL DPSK HETERODYNE TRANSMISSION

Indexing terms: Optical communications, Optical transmission, Polarisation, PSK

An optical DPSK transmission experiment was performed at a bit rate of 1·2 Gbit/s using a dual-balanced polarisation-diversity receiver. A high receiver sensitivity of less than −42·8 dBm was achieved and the power penalty due to polarisation diversity was analysed.

Introduction: In a coherent lightwave transmission system, overcoming signal fading caused by polarisation fluctuation in the transmitting fibre is crucial for a practical system. Among several possible solutions polarisation diversity reception[1] is the most attractive, considering its high-speed response and that it is easily applicable in an optical frequency division multiplexing system.

We developed a dual-balanced polarisation-diversity receiver (DPR) using two balanced receivers,[2] and demonstrated 1·2 Gbit/s optical DPSK transmission. The IF was monitored and stabilised through the novel AFC method described below.

Receiver: Fig. 1 shows the system configuration for the 1·2 Gbit/s DPSK transmission experiment. The DPR is enclosed by broken lines. The received signal and local laser output were divided separately by polarisation beam splitters (PBSs) into two orthogonally polarised components. The components of the signal and local laser with the same polarisation were then mixed in the polarisation-maintaining fibre couplers (PMCs). The output pair from the couplers was detected by a pair of dual-detector balanced optical receivers (DBORs). Each PBS has an extinction ratio of greater than 20 dB and an insertion loss of about 2 dB.

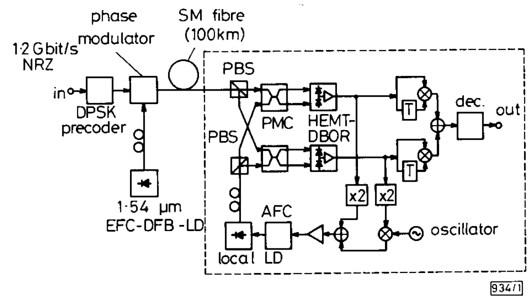

Fig. 1 *Configuration of 1·2 Gbit/s DPSK transmission experiment*

In the DBOR we used a wideband low-noise HEMT as the front-end amplifier. The IF signals generated were demodulated separately by a delay-line demodulator, then summed and passed through a low-pass filter to regenerate the baseband data signal.

When we recombine two signals at the baseband stage, it is not easy to extract the IF signal stably for AFC. If we simply combine the two IF signals extracted from two branches of the diversity receiver, the combined signal for AFC disappears when the IF signals are equal in amplitude and have a phase difference π. To overcome this problem, two IF signals were extracted separately, then one of these signals was modulated at a low frequency (20 kHz) before combining.[3] With this scheme the combined IF signal does not disappear even when both IF signals have the phase difference π, because the phase of the combined signal changes periodically with the frequency of the extra modulation. The frequency of the extra modulation should be sufficiently higher than that of the AFC loop response.

Transmission experiment: In the transmission experiment, an external-fibre-cavity loaded DFB laser module operating at a 1·54 μm wavelength[4] was used as the signal and local oscillator source. The signal light was modulated by a straight-line, travelling-wave type $Ti:LiNbO_3$ phase modulator with a 1·2 Gbit/s DPSK encoded NRZ ($PN: 2^{15} - 1$) signal. The modulated optical signal was transmitted through a conventional 100 km single-mode fibre (0·19 dB/km) and detected by the DPR. The IF signal was fed back to a PZT voltage translating the external fibre cavity of the local laser. The IF centre frequency was stabilised to $2·4 \pm 0·006$ GHz.

Results: The experimental bit error rates are shown in Fig. 2. We measured for polarisation states corresponding to: (i) all signal light incident on one balanced receiver (○); (ii) all light incident on the other receiver (□); (iii) light equally divided

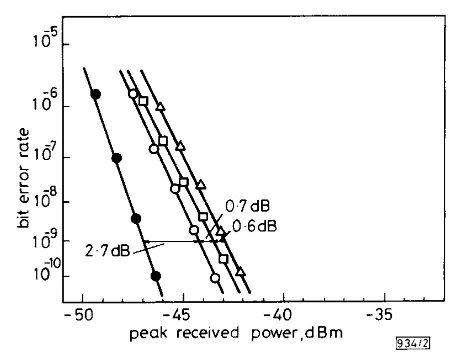

Fig. 2 *Bit error rates from experiment*
1·2 Gbit/s, DPSK, polarisation diversity

	receiver 1	receiver 2
○	1	0
△	0·5	0·5
□	0	1
●	Single-channel operation	