A 2 (Plenary)

Integrated Fibre Circuits - Prospects and Possibilities

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1. Introduction

Optical fibres are well established in the domain of point-to-point telecommunications, where they demonstrate the advantages of very wide bandwidth, low attenuation, low weight and cost, and immunity to electromagnetic interference. Passive fibre components, such as four-port couplers for signal distribution or wavelength multiplexing, have emerged allowing increased exploitation of the available bandwidth or application in local-area networks and all-optical signal processing circuits. The advent of special amplifying fibres has provided transmission over effectively lossless channels, and has further driven the development of many peripheral passive components. Examples are fused-fibre couplers for amplifier pump multiplexing, fibre gratings for pump filtering or suppression of amplified spontaneous emission (ASE), and inline isolators to allow high gain and reduced gain ripple. Complementing advances in fibre amplifiers are fibre lasers that can convert poor-quality light from semiconductor devices into low-noise, single-frequency sources with the potential for broad tunability and high output power.

Optical fibre devices have many attributes which render them attractive as building blocks for more complex optical systems. Low-loss polarisation-independent connections between different fibre devices may readily be made, due to similarity of geometry, materials, and modal characteristics. In comparison with integrated-optical systems, the complete containment of light in the fibre makes the optical system relatively robust, simple to align, and free from mechanical disturbances. While the connection of devices within a circuit is potentially even simpler and cheaper in a planar waveguide technology, the connection of external devices to planar circuits is still subject to some difficulties. In common with micro-optic technology, however, fibre circuitry also offers the advantage of separate optimisation of the materials and processing of individual components before the construction of the complete system, thus removing the compromises which must be made in monolithically integrated schemes. In addition, the integration of large numbers of components on an integrated optical "chip" has been held back by the occurrence of high losses at tight bends in dielectric waveguides, a problem which may be avoided in fibre circuitry if the area taken up by the circuit is not a significant limitation.

The astounding revolution in microelectronics since the 1960's is due in part to the concatenation of many simple components to perform extremely complex functions. This interconnection requires a minimum output level from each individual element to enable it to drive the next one, so that each element must present at least unity gain at its output for the system to function. The advent of optical fibre amplifiers and oscillators as simple, easily interconnected, circuit elements and the rapidly increasing range of special optical fibres and novel fibre components, is leading to a new technology of integrated fibre circuitry which rivals both planar waveguide circuits, as well as hybrid or microptic technologies, to realise complex all-optical functions. Recent advances in novel fibres and fibre devices, and examples of their application in integrated fibre circuitry, are described in this paper.

2. Active Fibre Devices

Fibre lasers

The first important active fibre device to be demonstrated was the fibre laser, which consists of a short length of fibre in which rare-earth ions have been introduced into the core, with mirrors placed at each end. The ions are pumped by an optical source, often a laser diode, via an absorption band into a metastable state. Spontaneous emission from this state may then be amplified by stimulation of further transitions, and the mirrors provide feedback allowing oscillation to occur. A large range of rare-earth dopants is possible, resulting in operation at wavelengths from 400nm in an upconversion scheme, to 3.5μm in an erbium-doped ZBLAN fibre.

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The confinement of the pump radiation in the waveguide allows high pump intensity, and thus a high level of population inversion, to be maintained over long lengths for low pump power, and the close overlap of the signal and pump radiation with the ion distribution ensures high-efficiency. A particular advantage of fibre lasers over direct use of the pump laser radiation, is that the fibre laser can convert poor-quality, noisy, optical output from a semiconductor diode, into quiet, single-frequency, radiation which may be tuned over a broad bandwidth. Fibre lasers are capable of higher pulse output powers than diode lasers, and fibre amplified pulse powers up to 110kW has been observed.

Neodymium-doped fibre lasers operating at 1 300nm and erbium-doped fibre lasers at 1 500nm, combined with photorefractive gratings, have exhibited single-frequency operation appropriate for WDM systems. Modelocked fibre lasers have produced 30fs pulses suitable for spectroscopic applications, whilst in other soliton systems, pulse repetition rates up to 200GHz have been obtained using dispersion-tapered fibre. Rare-earth-doped planar waveguide lasers based upon glasses and crystals may also be appropriate drivers for fibre circuits, and a large number of erbium and neodymium-doped lasers have now been demonstrated, including line-narrowed, tunable, ring, Q-switched and modelocked configurations.

Fibre amplifiers

Erbium-doped fibre amplifiers (EDFA's) can provide polarisation-insensitive gain of more than 50dB and output power of 0.5W at wavelengths around 1500nm, where silica-based fibres have minimum attenuation. The 3dB gain bandwidth of an EDFA is typically 3-8nm, but can be increased to more than 30nm by gain-shaping techniques. At bit-rates above 0.1Mb/s EDFA's are immune to intersymbol interference, and in FDM systems with carrier spacings above 100kHz, crosstalk is negligible. Due to ease of obtaining a high population inversion, the noise figure may approach the theoretical minimum of 3dB when pumped at 980nm simultaneously with a gain of over 50dB. The gain-slope efficiency of an EDFA is typically 11dB per mW of pump power at 980nm. The EDFA can operate as a small-signal amplifier, power amplifier, preamplifier, or power limiter, and gain can either be localised to a few metres or can be distributed along the entire length of the fibre.

A simple amplifier circuit consists of the erbium-doped fibre, a dichroic coupler to multiplex the pump with the input signal, and the pump laser diode. More sophisticated systems include pump filters to remove, or return, the unused pump at the fibre output, filters to suppress

ASE and flatten the gain spectrum, and isolators to remove unwanted reflections or backscattering.

Harmonic generation

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Glass is a centro-symmetric material and was not expected to be capable of second harmonic generation. However, it has been demonstrated that high optical fields can generate periodic non-linearities. By phase matching the fundamental and second harmonic waves in the fibre core an efficiency of 13% in generating 0.53μm radiation from the input 1.06μm source has proved possible

3. Passive Fibre Devices

Fibre couplers

Fibre couplers perform the function of division and distribution of power in a fibre circuit. This division may be independent of wavelength and polarisation, as in the case of a star coupler in distributive networks. On the other hand it may be designed to couple a specific band of wavelengths from one fibre to another, as in a pump multiplexer in an EDFA circuit. Fused couplers, formed by twisting two monomode fibres together, heating in a short region until the fibres fuse, and pulling to taper them down into a coupled structure, are the most widely used. These devices are well-suited to application as pump multiplexers and filters in EDFA's, but planar devices based upon glass are emerging as strong contenders where wavelength- and polarisation-independent distribution of signals to more than four output fibres is required.

Acousto-optic modulators

All-optical processing is an attractive goal, but there is clearly a requirement for fibre circuits to interface with electronic circuits, preferably without the optical signals leaving the fibre environment. All-fibre acousto-optic devices have been applied as phase modulators in an FM mode-locked Nd-doped fibre laser, where pulses of 200ps duration with repetition rate of 417MHz and peak power of 180mW have been observed. Recently a new design of efficient all-fibre acousto-optic transducer employing acoustic focusing has been demonstrated. A phase modulation of 2.63 radians at an optical wavelength of 1550nm was obtained at an RF frequency of 86MHz and a power of lW.

In-line isolators & circulators

In-line fibre isolators, using micro-optic technology, with >30dB isolation and 0.5dB forward attenuation are commercially available for use with optical amplifiers operating at around 1500nm. At present, all-fibre isolators do not exhibit comparable isolation, but improvements in fibres to produce high Verdet constants may improve their future prospects. A very interesting development in this respect is the recent report of an "isolator chip" mounted between the ends of two thermally-expanded-core fibres. The chip consists of two birefringent plates and a Faraday rotator. Despite being 1mm thick and lacking a waveguide structure the diffraction losses introduced by the chip are negligible because of the x3 expanded spot size. Measured insertion and reverse losses are 2.5dB and 40dB at 1.55μm and the device is capable both of further improvement and mass production.

Pulse-shaping fibres

A recent development in fibre components for pulse-shaping, of particular interest to the generation of ultra-fast soliton pulse streams, is the dispersion-tapered fibre. In a recent demonstration, a 1.6km length of fibre had a dispersion at 1550nm that was tapered from 10ps/nm km at the input end to 0.5ps/nm km at the output. Sinusoidally amplitude-modulated light, resulting from tunable beating between the output of two DFB lasers emitting at 1550nm, when introduced at the input end was converted into high-quality soliton pulses at a repetition rate up to 200GHz, and with durations as short as 230fs.

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Fibre gratings

Rapid progress has recently been made in the direct writing of gratings into fibres. Gratings with a reflectivity of 99.8% have been holographically written into the core of a germania-doped fibre with a 20ns pulse of uv light. They have also exhibited linewidths as low as 6GHz and as high as 920GHz. Such gratings have enabled line-narrowed fibre lasers to be realised as noted above, and will become powerful in-line integrated fibre components for channel filters in WDM systems. In the past, gratings formed by polishing and etching fibres have been used for pump filtering and gain-shaping. One example provides 99% reflectivity over a 22nm bandwidth at either 980nm or 1480nm with an insertion loss less than 0.5dB between 1510 and 1560nm. An alternative configuration has involved compressing fibres between corrugated plates.

Photorefractive gratings represent a far more attractive technology for convenient in-line filters due to their robustness, and hold out the potential for chirped and shaped filters and dispersion compensators, and so on. One drawback of this technique has been the need to remove the uv-absorbing primary coating from a length of fibre to create the gratings, with the consequent danger of reducing the strength of the structure. The recent demonstration of Bragg gratings written by single pulses from an KrF excimer laser during fibre drawing demonstrates the feasibility of on-line mass production of these devices and retains the strength of the fibre, because the gratings are formed before the primary coating is applied. The addition of robust, design-and-write, filters to the catalogue of available fibre components will have an enormous impact upon integrated fibre circuitry.

Tunable fibre Fabry-Perot resonators

Grating resonators may be tuned by about 2nm through application of strain in a phenomenon which has been successfully exploited in the realisation of discrete strain sensors. Larger tuning ranges and similar bandwidths are obtained from all-fibre Fabry-Perot etalons where a broad wavelength range must be interrogated. Such a resonator with a free spectral range of 43nm and a bandwidth of 0.38nm, in which the wavelength of transmission was tuned by piezoelectric elements, has successfully interrogated four fibre-grating strain sensors placed along a single fibre. The optical source driving the sensing system was an erbium-doped fibre superfluorescent source, coupled to the sensing fibre with a 3dB fibre coupler, which directed half the power reflected from the fibre gratings to the fibre Fabry-Perot resonator. Broadly-tunable all-fibre Fabry-Perot resonators clearly occupy a complementary position to fibre gratings in wavelength-encoded integrated fibre circuitry.

4. New Fibre Materials and Devices

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Considerable research is underway at the present time on new materials, some of a revolutionary kind, for fibres. These range through novel glasses, glasses with low phonon energies, slightly crystallised fibre cores and the introduction of small local phases, which may not even be glasses, comprising a radically different structure in suspension in the glass host. Poling of the fibre core glass has already been shown to produce an effective linear electro-optic effect so that fast electro-optic switching and tuning of fibre lasers is a possibility. Poling can also provide greatly enhanced second-order susceptibilities in glass. As well as very efficient harmonic generators one can look forward to widely-tunable fibre parametric oscillators, as well as electrically-tunable fibre couplers, gratings and modulators. With these, and other, forseeable research advances a wide range of fibre components is predictable.

5. Integrated Fibre Circuits

Already a large catalogue of all-fibre or hybrid fibre components and circuits is available, particularly for telecommunications. Long-distance communication is possible at large bandwidth and effectively zero loss with the pumping power provided by fibre lasers powered by semiconductor laser diode arrays. Optically-activated optical switches have been demonstrated, albeit still requiring some improvement, whilst lossless many-way splitters capable of being switched are feasible. Fibre frequency-comb lasers can generate many equally-spaced wavelengths for WDM and other systems. All-fibre sub-systems have generated soliton pulses as short as 30fs and rates up to 200GHz. All-fibre distributed sensors are commercially available in which the only electrical input is to the pump source for the fibre Q-switched laser and the acousto-optical switch. Frequency-agile fibre lasers and programmed gratings written in the fibre during fibre drawing will extend the flexibility and range of applications considerably.

6. Conclusion

Only a few years ago the concept of integrated all-fibre circuits and systems was no more than a gleam in the eye. However, the idea has been gestating rapidly and can now be said to have emerged into the light of day. It will grow rapidly from a clumsy, tentative, youthful phase into a mature technology.