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Fibre-based short pulse generation and shaping technology

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Introduction

The development of the erbium doped fibre amplifier has resulted in tremendous increases in transmission capacity over the past few years with demonstrations of error free data transmission at single channel bit rates as high as 200 Gbit/s using OTDM technology [1]. Soliton transmission arguably offers the greatest potential for exploiting the enormous transmission capacity of EDFA based transmission lines with impressive demonstrations over both transoceanic and terrestrial distances [2,3]. Further advances should continue to be made with the refinement of advanced soliton control techniques [4,5]. A key issue when pushing transmission capacity to the limits is the development of stable pulse sources capable of generating pulses of an appropriate form (e.g. shape, duration, repetition rate and wavelength), and of sufficient quality (e.g. transform-limited, low-jitter) so as not to limit the attainable transmission distances. Both semiconductor and fibre based generation schemes are an option, each with relative merits and disadvantages. Semiconductor based pulse schemes, e.g. gain-switched laser diodes, MQW modulators, offer advantages of simplicity, compactness and stability but can suffer limitations regarding the range of output pulse forms attainable, pulse quality and broadband tunability. Conversely, fibre based pulse generation offers high pulse quality, wider operating regimes, e.g. shorter pulse durations, higher powers, novel pulseforms, and broadband tunability but suffers in terms of device compactness and stability.

In this paper we review the current state of development of fibre based pulse generation technology for communication applications describing the principal fibre based short pulse generation techniques so far demonstrated. In addition, we discuss the option of using novel fibre componentry, e.g. controllably chirped fibre gratings, dispersion varying fibre, to extend and improve the performance of semiconductor/integrated optics based short pulse sources. Such hybrid systems which exploit both the flexibility of the fibre approach and the stability of semiconductors seem the most likely fibre based sources to find real world application.

Modelocked fibre lasers

To date three basic mechanisms for the mode-locking of fibre lasers have been developed: active [6-13] and passive mode-locking [14-22] and sliding frequency soliton generation [25-27]. A large number of cavity configurations and realisations have been demonstrated for each particular technique. Active mode-locking is by far the most appropriate technique for telecommunication applications. Generally a unidirectional ring geometry is selected (see Fig.1) and an electro-optic, integrated-optic amplitude or phase modulator incorporated to provide the required modulation. (Note also, that all-optical modulation can be used by injecting a train of pulses into such a laser cavity through Cross Phase Modulation (CPM) [12] and has potential for all-optical clock recovery and all optical regeneration [13]). An optical filter is usually incorporated within the cavity to provide both spectral control and/or device tunability. Additional componentry is also frequently required for device stabilisation. Transform-limited soliton and Gaussian pulse generation at telecommunication relevant repetition rates ranging from 2.5-40 GHz has been widely reported in the literature. Pulse durations are typically in the range ≈2-50ps dependent principally on repetition rate, intracavity dispersion, nonlinearity and filter strength. Most effort has been devoted to repetition rates < 10 GHz, 10 GHz representing the maximum modulation base rate currently envisaged for OTDM based high speed systems with pulse durations as short as 2.5 ps achieved. Continuous wavelength tunability of up to 60 nm has been obtained with minimal variation in performance across the tuning range (see Fig.2). Typical average output powers are in the range 0-10 dBm.

Unfortunately, there are a number of complications that require addressing when constructing an environmentally stable laser, these arise primarily due to the long device length. Co-operative upconversion effects with erbium doped fibre limit the maximum erbium ion concentration to ≈1000 ppm and restrict the minimum cavity length to ≈5-10m. Laser operation at repetition rates of interest (typically 10 GHz) therefore requires harmonic mode-locking at a very high harmonic of the cavity round trip frequency and this can lead to problems with supermode competition and instabilities within the laser. Generally additional steps need to be taken, e.g. incorporation of an additional sub-cavity [7], or low-frequency cavity length dithering [8], to ensure the dominance of a single supermode. Furthermore, the resonant nature of the mode-locking process requires a very accurate matching of the modulation frequency to the cavity length. Since the effective cavity length is extremely sensitive to environmental changes e.g. temperature, this matching has to be actively controlled. A number of options have been reported: active cavity length stabilisation to a fixed modulator frequency [8,9]; electronically phase-locked loop to allow the RF drive to track the cavity length change [11]; and finally accurate temperature stabilisation of a single polarisation state cavity [6,10]. Each with reasonable success, albeit with a resulting increase in system complexity. To date these lasers have generally been constructed from conventional SM components. However, due to the long cavity length any practical device will need to be constructed from 'exotic' Polarisation Maintaining (PM) components, e.g. doped fibres and WDMs, to reduce the impact of environmental stability [6,10]. It can thus be appreciated that an adequately stabilised actively mode-locked fibre laser is in reality a rather complex and correspondingly costly device. However, the pulse quality and performance of such lasers is excellent and they have consistently outperformed rival semiconductor based sources in the most stringent tests i.e. long distance soliton transmission experiments. Note, however, that the development of soliton control techniques [4,5] have reduced the pulse quality requirements previously needed since the system effectively reshapes the input pulse to the optimum form with negligible penalty. The use of relatively complex fibre lasers in these controlled systems is therefore unlikely to be favoured.

A second option for fibre based short-pulse generation is passive mode-locking whereby some form of nonlinear element e.g. Nonlinear Amplifying Loop Mirror (NALM) is incorporated within the laser cavity [14-22]. Such lasers are more appropriate for the generation of pulses considerably shorter than those obtainable using active techniques (<1ps) and as such are generally unsuitable for direct transmission applications. Moreover, such lasers are susceptible to timing and spectral instabilities [15,18,23,24], although these undesirable effects can largely be countered by the incorporation of additional filters and timing elements within the cavity e.g. a phase modulator [21], or for example by self-stabilisation through the soliton electrostrictional effect [22]. Although unsuitable for transmission application such sources can be useful as convenient simple laboratory sources of ultrashort optical pulses for component testing and validation. Pulse durations in the range ≈10ps to 70 fs have been obtained at repetition rates typically in the range 1-100 MHz. Pulse energies are generally in the range ≈1pJ-1nJ.

One final laser option for short pulse generation is based on the sliding filter technique developed for soliton control in soliton transmission lines [4] and has become known as the sliding frequency soliton laser [25-27]. Pulsed operation within such lasers is obtained by frequency shifting and filtering of radiation circulating within the cavity: cw radiation is continuously frequency shifted as it circulates around the cavity and experiences high loss whereas pulsed radiation can reshape itself spectrally due to the combined effects of dispersion and nonlinearity so as to cancel the shifting/filtering effects. The cavity loss is therefore less for pulsed operation and this is therefore the preferred lasing regime. The technique leads to advantages in terms of self-start threshold and permits harmonic mode-locking. 7ps, 20 GHz pulse generation has been reported but the lasers suffer from many of the instabilities observed within passive mode-locking schemes [27]. It therefore once again unlikely that they will find use in any practical system.

To summarise, mode-locked fibre lasers can be constructed to cover a wide range of pulse requirements and can deliver pulses of excellent quality. Active mode-locking represents the best option for the development of a practical, stable fibre based short pulse telecommunication source. However, the additional complexity required to develop a truly stable device is likely to hinder their widespread practical field usage in the short term unless pulse quality, ultrashort pulse durations (≈< 5ps) or, broadband tunability is of absolute fundamental importance. Their application as laboratory pulse sources for advanced telecommunication research is however beyond question.

Beat signal conversion techniques

A second range of possible pulse generation techniques is based upon the all-optical transformation of a high-frequency optical beat signal into a train of optical solitons via nonlinear propagation in a dispersion varying fibre circuit. The repetition rate of the pulse trains is defined by the frequency of the beat signal at the source input and the final Mark-Space-Ratio (MSR) by the variation in dispersion along the fibre length [28]. Transform-limited pulse generation at repetition rates in the range 30-200 GHz have been directly demonstrated using such techniques at MSRs of typically 10:1 [28-33]. The merit of the technique lies in the fact that it is non-resonant in nature leading to increased environmental stability relative to fibre based mode-locking techniques with continuous and broadband repetition rate and wavelength tunability. The principle disadvantage is that it is only really appropriate for ultra-high repetition rates ($>$30 GHz) due to the requirement for adiabatic pulse compression, and therefore gradual fibre dispersion variation, along the fibre length [28]. This requires prohibitively long fibre lengths ($>$10 km) in order to access lower repetition rates (longer pulse durations). This restriction to higher repetition rates leads to difficulties when interfacing such sources to the electrical domain e.g. for synchronisation and data encoding for which 40 GHz operation really represents state of the art. Further issues relating to these sources that need to be addressed include: elimination of phase noise between the input beat signal components which can manifest itself as timing jitter at the system output; and since the technique relies upon the propagation of high intensity narrow-linewidth signals over long distances for its operation, elimination of stimulated Brillouin scattering. Despite these drawbacks technical solutions to the aforementioned problems have been demonstrated in the laboratory [31,32].

We have developed a stabilised, diode-driven beat-signal conversion source (see Fig.3) in conjunction with co-workers at BT Labs. (Work performed within European Union RACE project R2015 "ARTEMIS"). Low timing jitter is obtained by generating the two spectral components (separated by $\approx$ 40 GHz) required at the system input from a single DFB laser by use of a 20 GHz amplitude modulator tuned to a transmission null and driven with 20 GHz RF. The corresponding timing jitter is fully determined by the RF source and has been measured to be $<$300 fs at the system output. Brillouin scattering is eliminated by phase modulation of the DFB laser. This effectively broadens the DFB laser spectrum relative to the Brillouin linewidth thereby increasing the Brillouin threshold. This results in a systematic sweeping of the central wavelength of the source ($\approx$100 MHz) but does not lead to additional timing jitter since both new spectral components generated are swept together, thereby preserving their frequency spacing and phase noise characteristics. The dispersion decreasing fibre followed a hyperbolic profile at 1550 nm tapering along the 8 km length from 13.75 to 2.75 ps/(nm.km). The profile and output dispersion were chosen so as to reduce the absolute physical length of fibre required to obtain high quality, adiabatic 40 GHz pulse generation at an MSR of 5:1, whilst maintaining a practical optical power requirement on the input beat signal (80 mW). The source produced soliton pulses of durations 4.5-6.5 ps at continuously tunable repetition rates in the range 32-40 GHz within the wavelength range of the available diodes 1547-1563nm (see Fig.3). The stability and quality of the pulses has been demonstrated in pulse propagation experiments over a 200 km dispersion shifted fibre transmission line incorporating 50 km amplifier spacing [32]. Due to the low jitter beat signal seed source we were able to perform clock recovery on the pulse train and to make electrical domain measurements [32]. Furthermore, using the clock recovery circuit we have recently been able to synchronise a 40 Gbit/s data stream (9ps pulses) with the soliton train and use this in conjunction with an all-optical modulator based on nonlinear polarisation switching in an optical fibre to impose error free real data on a 40 Gbit/s continuous wave soliton stream with minimal power penalty [33]. A typical modulated pulse stream (as measured on a 32 GHz pin diode and 40 GHz sampling scope) is shown in Fig.4. The results constitute the first demonstration of the modulation of the output of a beat signal soliton source and should enable a true appraisal of the suitability of such beat signal to soliton train conversion sources for future high frequency telecommunication applications. Furthermore fabrication technology for dispersion decreasing fibre has improved considerably over recent years and we have now performed controlled dispersion profiling over fibre lengths as long as 40 km [34] and dispersion profiles in the normal dispersion regime [35]. Such fibres also have applications in dark soliton generation [35], pulse compression [36] and advanced high speed soliton transmission [37].

To summarise beat-signal conversion sources (both bright and dark pulse) can be constructed for operation at high frequencies (>30 GHz) exhibiting good environmental stability, high pulse quality, ultra-low jitter and both continuous repetition rate and wavelength tunability. Synchronisation and modulation issues can be overcome but only at a considerable increase in cost and complexity although this could in principle change with future advances in high speed electronics.

Hybrid semiconductor-fibre sources

Fibre pulse sources can generate high-quality pulse forms with an enormous performance parameter space, however stabilisation and/or synchronisation issues are likely to limit their practical application in real world communication systems. Their applications are still very much as convenient tools for laboratory research usage. However, research into fibre based short pulse generation has resulted in a number of novel fibre components and techniques which may be of more immediate real-world use when used in conjunction with semiconductor based sources. Examples of such components include controllably chirped fibre gratings and highly dispersive fibres which can be used as lumped dispersive elements for the elimination of residual chirp as well as spectral filtering e.g. for use in conjunction with gain switched diodes or EA modulator based pulse generation schemes [38,39], and dispersion decreasing fibre which can be used to gain access to shorter pulse durations with semiconductor devices through adiabatic pulse compression [39]. A final impressive example concerns WDM sources based on supercontinuum generation of amplified gain switched laser pulses (or alternatively pulses from an actively mode-locked fibre laser) in dispersion shifted fibre [40]. A multi-channel pulse stream is obtained by spectral filtering of the supercontinuum pulses. Up to forty 6.3 GHz pulse streams have been simultaneously generated in this fashion each exhibiting ultra-low timing jitter and crosstalk and have been used in ultra-high capacity transmission experiments. Such hybrid schemes therefore seem to offer the best of both worlds: the compactness of the active/resonant element resulting in reduction of environmental stability issues to a manageable level, and the flexibility and extended performance range of the fibres.

Conclusions

Considerable advances in fibre based short pulse generation techniques have been made over the past few years; each with their own merits and drawbacks. Fibres have clearly been shown to provide a unique, powerful and flexible environment for the generation of ultrashort pulses. From a telecommunication perspective it is clear that actively mode-locked fibre lasers represent the best all-fibre option and that such systems can be designed to give excellent performance characteristics. However, such devices are compromised by stability issues. These can be overcome but add cost and complexity. It is this drawback that is most likely to limit their future widespread field application. Their suitability for advanced laboratory application is however clearly beyond question. Non-resonant, nonlinear fibre optic techniques are of interest from a research perspective but are still too complex and untested to warrant serious consideration at the current time. In the short to medium term fibre techniques are most likely to find real system application when used for pulse 'shaping' in conjunction with semiconductor based pulse generation schemes where they can be used to: improve pulse quality, to extend device performance and, to generate specialised/novel pulse forms.

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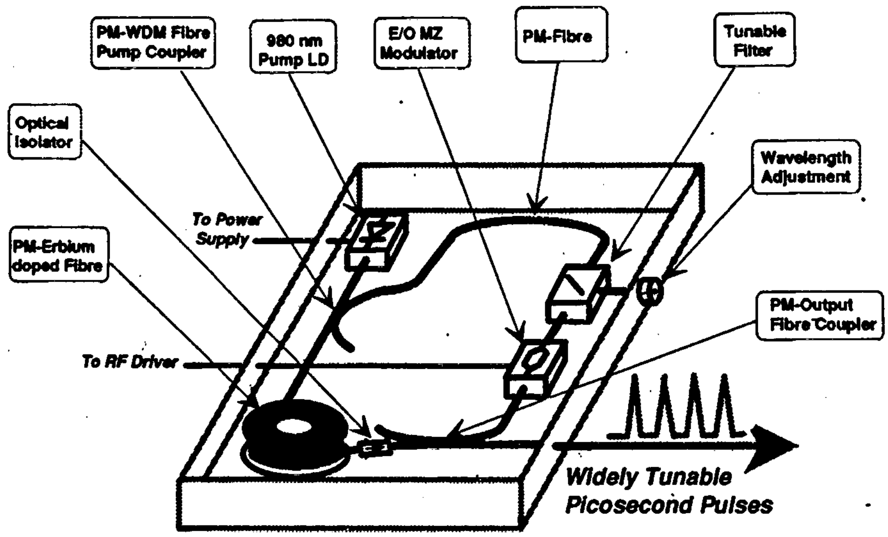

Fig.1 Schematic of packaged, environmentally stable, actively mode-locked, PM fibre laser developed within RACE project R2015 "ARTEMIS". (Courtesy of G. Veith, SEL Alcatel).

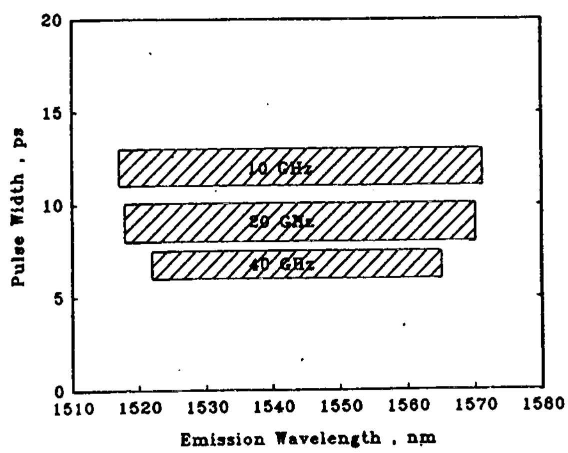

Fig.2 Tunability and performance characteristics of the packaged device shown in Fig.1 (See Ref[10]) illustrating tuning range and pulse width for modulation frequencies of 10, 20 and 40 GHz.
(Courtesy of G.Veith, SEL Alcatel)

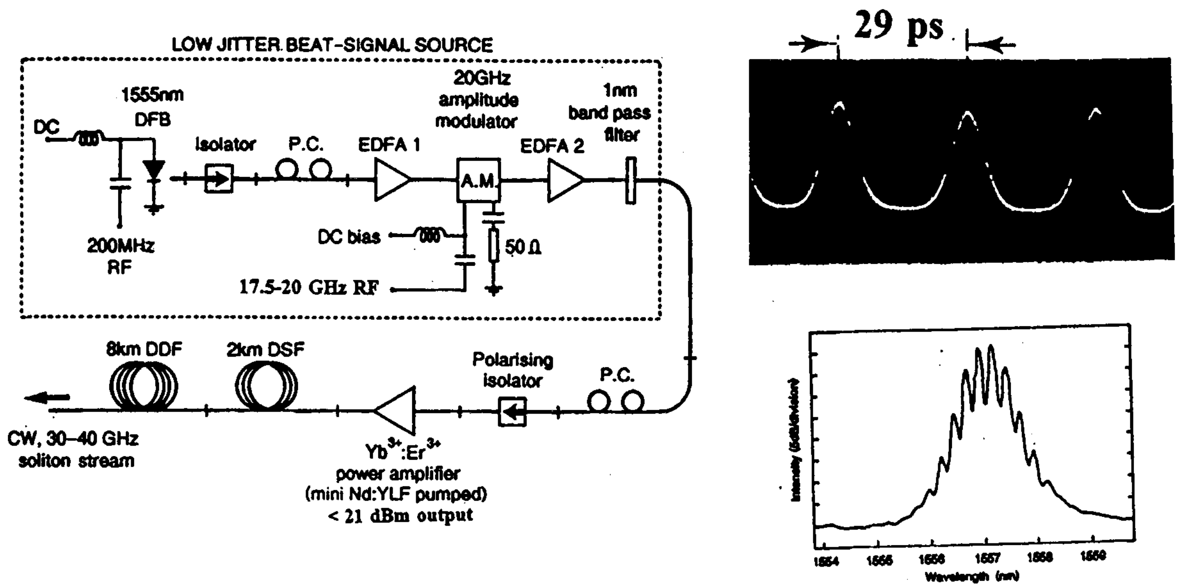

Fig.3 Low-Jitter, diode-driven, 40 GHz beat signal conversion source capable of 32-40 GHz, 4.5-6ps soliton generation developed with RACE project R2015 "ARTEMIS" [32] with inset of autocorrelation and spectrum of 35 GHz, 5.0ps pulse train.

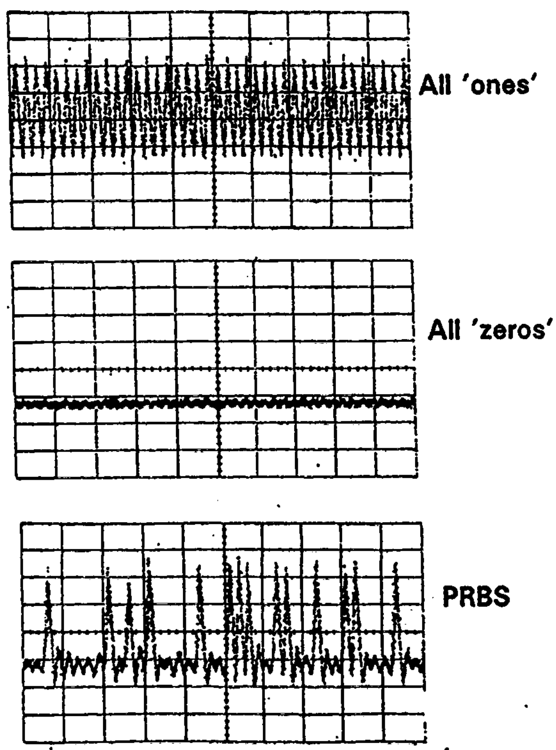

Fig.4 Modulated soliton stream from the source illustrated in Fig.3. Direct, 40 Gbit/s, error free, modulation is performed using an all optical switch and synchronised data stream [33].