# Femtosecond pulses at 20 GHz repetition rate through spectral masking of a phase modulated signal and nonlinear pulse compression

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**Abstract:** We present a laser system capable of producing 190 femtosecond pulses at a repetition rate of 20 GHz. The spectral masking of a phase modulated diode laser is used to produce a train of picosecond pulses which are compressed using a fibre-grating compressor followed by subsequent adiabatic soliton compression to the femtosecond regime using a tapered photonic crystal fiber.



**OCIS codes:** (060.4080) Modulation; (060.5060) Phase modulation; (060.5530) Pulse propagation and temporal solitons; (190.4370) Nonlinear optics, fibers.

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## 1. Introduction

High repetition rate (tens of gigahertz) pulsed laser sources are of increasing importance due to their application in the field of optical frequency metrology [1]. Such sources can be realized in the 1 $\mu$m wavelength region using fiber integrated technology through the active modelocking of laser cavities [2], control of intra-cavity modulation instability [3] or through extra-cavity amplitude modulation of a continuous wave (CW) signal. Amplitude modulation using, for example, Mach-Zehnder amplitude modulators or electro-absorption modulators can achieve high repetition rate modulation, although the latter of these devices is not readily available at 1 $\mu$m, and both suffer from the fact that they require a DC bias offset to their voltage supply to ensure correct pulse shaping. The required DC bias will drift with environmental conditions, and so it is often necessary to actively control this offset.

By contrast, here a CW signal is converted to a 20 GHz repetition rate train of 9 ps pulses utilizing the little used technique of spectral masking of a phase modulated signal (SMPM) [4] - a bias-free method of modulation. The generated pulses are then compressed to a duration of 190 fs using a combination of a fiber-grating compressor and adiabatic soliton compression in a dispersion-decreasing photonic crystal fiber.

## 2. Pulse train generation through spectral selection of a phase modulated signal

The SMPM concept, a fuller description of which can be found in [4], is based on the introduction of a time varying optical frequency shift of the CW signal, and is illustrated graphically in Fig. 1. This is achieved through the use of a lithium niobate phase modulator (LNPM) which will impose a sinusoidal phase shift to the signal. Due to the relationship between the instantaneous phase shift with the shift in optical frequency, $\triangle\omega = \partial\Phi/\partial t$, this will result in a cosinusoidal instantaneous shift to the optical frequency. A spectral mask can then be applied to the signal, by use of a band pass filter, to suppress all but the frequency extrema of the signal, resulting in a train of short pulses at a repetition rate set by the frequency of the sinusoid applied to the phase modulator. This is conceptually similar to the generation of short pulses where the phase modulation is applied, not by a phase modulator, but instead by self phase modulation [5], or through cross-phase modulation applied by a co-propagating pulsed laser source [6].

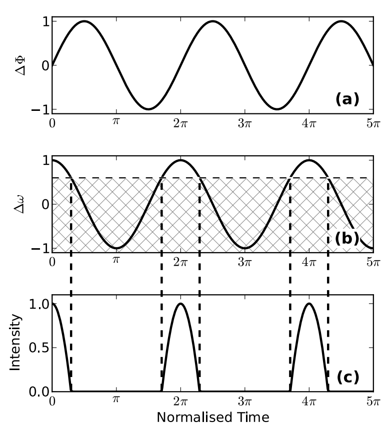


Fig. 1. Illustration of the principle of operation for the SMPM scheme. A sinusiodal phase shift (top) causes an instantaneous shift to the optical frequency (middle) upon which a spectral mask is applied using a band pass filter, the absorption of which is represented by the hatched area. This leads to the generation of short pulses (bottom).

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Importantly, the pulse shaping is achieved in the spectral domain through the overlap between the spectral mask and the frequency components generated by phase modulation. As such it is dependent only on the sinusoidal signal with which the LNPM is driven and hence can be considered a method of bias-free electro-optic intensity modulation and so does not suffer from the need for offset stabilization.

## 3. Method and results

The experimental set-up is illustrated in Fig. 2, and can be regarded as three separate stages. The first stage was the SMPM system which converted the CW output of a laser diode into a train of 9 ps pulses. The next stage was a fiber-grating compressor which compressed these pulses to 940 fs. The final stage comprised a dispersion decreasing photonic crystal fiber (DDPCF) in which the pulses were compressed to a duration of 190 fs through adiabatic soliton compression.

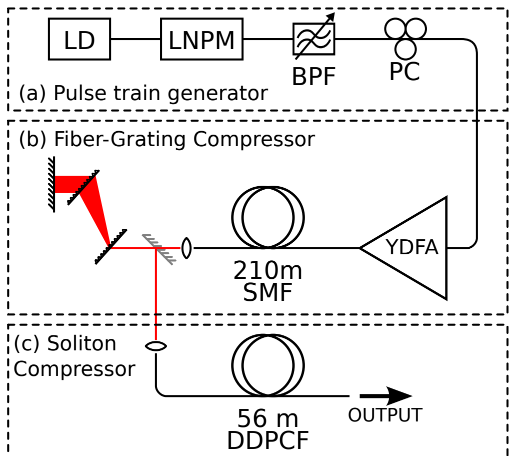


Fig. 2. System set-up. Key to acronyms - LD: Laser diode, LNPM: Lithium niobate phase modulator, BPF: Band pass filter, PC: Polarization controller, YDFA: Ytterbium doped fiber amplifier, SMF: Single mode fiber, DDPCF: Dispersion decreasing photonic crystal fiber.

Figure 3 shows the spectrum resulting from phase modulation of the laser diode before and after the band pass filter. The CW output of a laser diode operating at 1064 nm was modulated using a LNPM driven by a 20 GHz sinusoid with RF power of 27 dBm (corresponding to a peak to peak voltage of 7 V, or $3V_\pi$). This produced a comb of new frequency components at a spacing of 20 GHz, as shown by the gray curve. The central wavelength of this comb of frequencies was set by the CW diode laser, which was a temperature-controlled external fiber Bragg grating stabilized semiconductor diode (IPG Photonics), and the comb spacing was set by the RF drive to the phase modulator. A band pass filter (BPF) was used to select only the long wavelength components of the spectrum, shown as the black curve in Fig. 3(a). The BPF was a fibre connectorized interference filter with a center wavelength of 1064.8 nm and a bandwidth of 0.6 nm. The center wavelength of the BPF was adjustable by changing the angle of the interference filter. This was adjusted to ensure it overlapped with the edge of the comb spectrum, such that the bandwidth of the envelope of the resulting spectrum was 0.2 nm. This resulted in the generation of pulses at the 20 GHz repetition rate set by the sinusoid applied to the LNPM. The output from the BPF was measured using a SHG intensity autocorrelator (APE PulseCheck) and is shown in Fig. 3(b). This showed the output had been converted into a

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train of pulses with a deconvoloved full width half maximum (FWHM) duration of 9.0 ps, 1.1 times the transform limit. After the initial optimization of the BPF, the SMPM system required no further adjustment over many months, typically with multiple power cycles per day, whilst maintaining identical output performance.

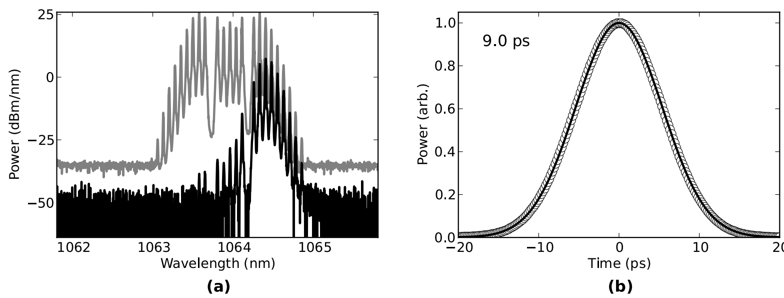


Fig. 3. **(a)** Optical spectrum of phase modulated output before (gray) and after (black) spectral masking using a band pass filter. **(b)** Intensity autocorrelation of output pulses after spectral masking on the phase modulated signal. A Gaussian fit implies a deconvolved FWHM duration of 9.0 ps.

After the generation of the pulse train through SMPM, the pulses were compressed to femtosecond duration using a two stage compression scheme. The first stage was a fiber-grating compressor, a well established technique [7] for the compression of un-chirped pulses through the generation of new spectral components in a length of optical fiber, generating a chirped pulse which can be compressed using bulk diffraction gratings.

The output of the pulse train generator was amplified using an ytterbium doped fiber amplifier (YDFA) to increase the peak (time averaged) power of the SMPM output from 0.91 (0.17) mW to 28.1 (5.07) W, a sufficient power to result in SPM and broadening of the optical spectrum in a 210 m length of single mode fiber (SMF), as shown in Fig. 4. Due to normal dispersion in the fiber, the pulse was broadened to 16.5 ps, as shown by the gray curve in Fig. 4(b). A pair of diffraction gratings in a double pass configuration was used to compensate the chirp and compress the pulse. Each grating had a 75% efficiency, which gives a total transmission through the double pass configuration of 32%, resulting in a time averaged output power of 1.55 W after the grating pair. Chirp compensation using the gratings resulted in the pulse duration being reduced to 940 fs, as shown by the black curve in Fig. 4(b).

The second compression stage was based on adiabatic soliton compression in a dispersion decreasing photonic crystal fiber (DDPCF). Adiabatic soliton compression (ASC) exploits the robust nature of optical solitons to perturbations. Solitons are $\mathrm{sech}^2$ shaped pulses whose duration, $T_0$, is given by

$$T_0 = \frac{2|\beta_2|}{\gamma E} \tag{1}$$

where $E$ is the pulse energy and $\beta_2$ and $\gamma$ are the dispersive and nonlinear parameters of the optical fiber respectively. A soliton will adjust its duration to maintain this condition if any of these quantities change slowly compared to the characteristic soliton length, $z_0$, given by

$$z_0 = \frac{2\pi|\beta_2|}{\gamma^2 E^2}. \tag{2}$$

In a previous publication [8] we showed how the output of a SMPM system operating in the 1.55 $\mu$m region could be compressed using an Raman ASC scheme, where pulses are subject

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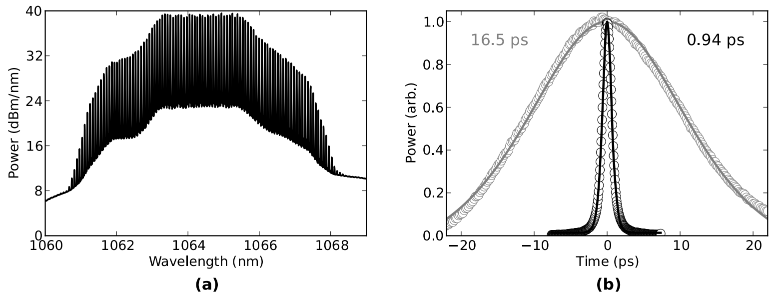


Fig. 4. **(a)** Optical spectrum of the signal after amplification and spectral broadening in single mode fiber. **(b)** Intensity autocorrelations of pulse output from the SMF in the fiber-grating compressor before (gray) and after (black) chirp compensation using the grating pair. Also shown are associated deconvolved FWHM pulse durations implied by autocorrelations.

to slow amplification in a multi-km length anomalously dispersive Raman amplifier. As the pulse energy, $E$, is slowly increased, the pulse duration will reduce according to Eq. 1, resulting in pulse compression. For systems operating at wavelengths longer than the material zero dispersion wavelength of fused silica of 1.27 $\mu$m, the requirement for an anomalously dispersive Raman amplifier can be experimentally realized using long lengths of step index fiber. A similar scheme based on Raman amplification of solitons at 1.06 $\mu$m, however, would not be practical as it would require km long lengths of photonic crystal fiber. Instead, our ASC scheme employs a dispersion decreasing PCF, that is, a PCF where the value of $\beta_2$ changes gradually along the fiber length.

The DDPCF was the same as that used in [9].Figure 5 shows the dispersion curves and cross-section scanning electron microscope (SEM) images for the input and output ends of the PCF. It was designed to maintain a near-constant effective mode area along the length of the fiber (3.0 to 2.8 $\mu$m$^2$), resulting in $\gamma$ remaining nearly constant, whilst the dispersion decreases from 42 to 9.8 ps$\cdot$nm$^{-1}$km$^{-1}$.

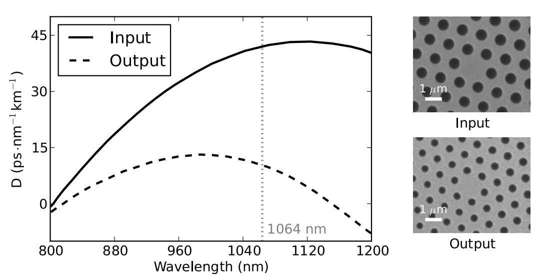


Fig. 5. Left: Dispersion curves for the input and output end of the dispersion decreasing PCF used in the adiabatic soliton compression stage. Right: SEM images of the input and output ends of the PCF.

To ensure the solitons were subject to adiabatic compression, it was important to ensure that they were launched into the DDPCF with a power matched to the fundamental soliton condition of the input end of the fiber. A soliton launched with a power greater than an integer multiple, $N$, of the soliton power would propagate, not as a fundamental soliton, but instead as a high-order soliton of order $N$, and we would expect the effects of high order soliton compression,

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which may have a significant deleterious effect on the output pulse quality.

As such, the output from the fibre-grating compressor was attenuated in free-space before being launched into the DDPCF to ensure the power matched the launch soliton condition. This was achieved empirically by adjusting the launch power whilst monitoring the output pulse autocorrelation. It was found that the optimum (time averaged) launch power was 170 mW, corresponding to a pulse energy of 8.5 pJ. For a pulse duration of 940 fs, this corresponds to an input soliton of order $N = 2.4$, suggesting that the pulses were launched as high order solitons. However, the pulses launched into the DDPCF were not transform limited, as they had not been completely dechirped by the grating pair. It is therefore more appropriate to consider the pulses in the spectral domain. Figure 4(a) shows that the launched pulses have a bandwidth of 2.9 nm, and considering instead the launch soliton condition for a transform limited pulse of this bandwidth, we find that the launched pulse energy corresponds to a soliton order of $N = 1.5$. As such, the pulses are expected to propagate as fundamental solitons. As the change in dispersion is gradual over the 56 m length of the DDPCF, compared to an input soliton length of 0.7 m, we expect adiabatic compression of the pulses.

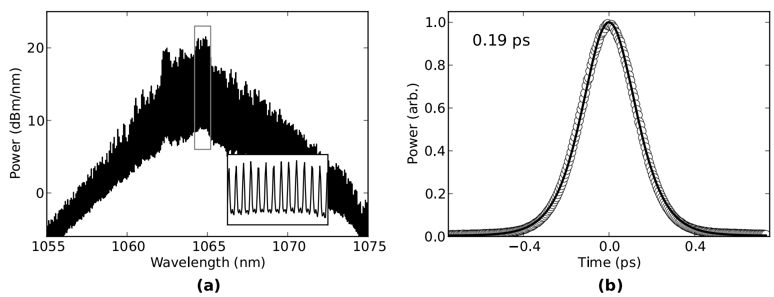


Fig. 6. **(a)** Optical spectrum of output from DDPCF compression stage. Inset shows zoomed-in section, revealing comb lines spaced at 20 GHz. **(b)** Intensity autocorrelation of output pulses from DDPCF compression stage. A sech$^2$ fit implies a deconvolved FWHM duration of 190 fs.

The spectrum and autocorrelation of the resulting output from the DDPCF are shown in Figs. 6(a) and 6(b) respectively. These show that the pulses were compressed to a duration of 190 fs, with corresponding broadening of the optical spectrum, which retains the 20 GHz spacing of spectral components, corresponding to the initial sinusoid supplied to the LNPM. The output autocorrelation also shows that the pulses are output with a low-pedestal sech$^2$ pulse shape, characteristic of adiabatic compression of fundamental solitons.

It should be noted that successful adiabatic compression relies on matching the input soliton condition for the DDPCF, and will continue along the length as long as the dispersion decreases provided the loss remains low. This raises the possibility that with advancing techniques in the fabrication of DDPCF of greater lengths, a more compact system may be envisioned where the output of the SMPM system is directly coupled to a longer length taper, which would enable direct compression of the pulses to the femtosecond regime without the need for an intermediate fiber-grating compression stage.

## 4. Conclusion

In conclusion, we have shown that the spectrally masked phase modulation technique can be used at 1.06 $\mu$m to generate a 20 GHz train of 9 ps pulses. These pulses were subsequently compressed to 190 fs using a combination of a fiber grating compressor scheme and an adiabatic soliton compressor based upon a dispersion decreasing photonic crystal fiber.

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