Terahertz, zero frequency error, tunable optical comb generator for
DWDM applications

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Dense wavelength division multiplexing (DWDM) is a promising method for exploiting the
enormous bandwidth of optical fibre. Accurate frequency control of many closely spaced channels
represents a key challenge in implementing such a system. An attractive approach is to injection lock a
group of DFB lasers to an optical comb \cite{1}. This method requires an exact microwave frequency spaced
optical comb. To date there have been reports of optical comb generators offering microwave frequency
spacings based on multifrequency lasers \cite{2}, Brillouin enhanced fibre lasers \cite{3} and phase modulation in
Fabry-Perot cavities \cite{4}, but none with the facility to tune arbitrarily the centre wavelength and line
spacing of the optical comb. Comb generators based on the use of an acousto-optic frequency shifter in an
amplified loop have also been reported but the limited frequency shift produced by the acousto-optic
device limits the spacing to at most a few GHz \cite{5}. In this paper we report on the first experimental
realisation of a simple, compact, all fibre, comb generator offering exact referencing to an arbitrary
supplied reference frequency and tunable microwave frequency comb-line spacing.

![Figure 1. Schematic of the fibre ring comb generator.](image)

A schematic of the comb multiplexing configuration is shown in Figure 1 and is the first
experimental realisation of a system proposed by Ho and Kahn \cite{6}. Comb generation is achieved by
successive phase modulation of the laser reference line in an amplified re-circulating loop. The resulting
optical comb has a spacing determined by the frequency applied to the phase modulator and absolute
frequencies determined by the reference laser. For precise channel definition a reference laser could be
used that is stabilised to an atomic or molecular line by using the optogalvanic effect \cite{7}.

In our experiments the centre wavelength was set using an external cavity tunable laser diode
(Anritsu MG9638A). The erbium doped fibre had a length of approximately 3 metres and was pumped at
980 nm using a MOPA with a launch power of 52 mW in fibre. The total length of the loop was about 10
metres. The comb-line spacing was set using a low phase noise synthesised microwave source via a power
amplifier giving an output power of 24 dBm. This drove a high-speed LiNbO\textsubscript{3} travelling-wave phase
modulator (model T.PM1-5.10 supplied by the Optoelectronics Division of the Sumitomo Osaka Cement
Co., Japan) with a $V_{ac}$ of around 4.7 volts.
The output spectra of the comb generator as the reference laser is tuned across the erbium window can be seen in Figure 2. For this measurement the modulation frequency applied to the phase modulator and hence the comb-line spacing was ~18 GHz, chosen to enable clear resolution on an optical spectrum analyser. An optical comb was observed for all reference wavelengths within the erbium gain bandwidth. To generate the maximum number of comb-lines, the modulation frequency applied to the phase modulator should be a harmonic of the round trip frequency of the fibre loop (~10 MHz in our case). As the reference laser approached the longer wavelength side of the 1,530 nm erbium gain peak there was also a noticeable increase in the number of comb-lines generated. With a reference laser wavelength of 1,532 nm 71 comb-lines were observed within a 40 dB envelope, corresponding to a comb spectrum width of 1.28 THz.

![Figure 2. Optical spectra from the comb generator as the wavelength of the reference laser is tuned across the erbium window. Reference laser power = 0.8 mW, modulation frequency = 18 GHz, resolution bandwidth = 0.08 nm, video bandwidth = 20 kHz.](image)

To measure accurately the comb-line spacing, the output of the comb generator was detected using a high-speed photodetector and the resulting beat signal observed using a microwave spectrum analyser. The frequency of the detected beat signal and therefore the comb-line spacing were found to correspond exactly with the frequency of modulation applied to the phase modulator. The electrical spectra of the beat signal with 11, 12.5, 14, 16, and 18 GHz modulation applied to the phase modulator can be seen in Figure 3. Good optical and electrical beat spectra were also measured for comb-line spacings from 2 to 25 GHz, with the upper frequency limited by the bandwidth of the phase modulator.
Figure 3. Superimposed detected beat spectra with 11, 12.5, 14, 16, and 18 GHz modulation applied to the phase modulator. Reference laser wavelength = 1,550 nm, reference laser power = 0.8 mW, resolution bandwidth = 1 MHz, video bandwidth = 3 kHz.

In conclusion, we have reported on the experimental realisation of a simple optical comb generator which enables accurate setting of the centre wavelength and comb-line spacing. Using a tunable laser as a reference we were able to tune the centre wavelength of the comb across the erbium window. With a comb-line spacing of 18 GHz and a centre wavelength of 1,532 nm, 71 comb-lines were observed within a 40 dB envelope. The flatness of the erbium doped fibre gain spectrum and ultimately fibre dispersion limit the number of comb-lines generated. It is expected that the number of comb-lines could be increased considerably through the use of dispersion shifted fibre and gain flattening techniques [8]. From these preliminary results we expect this simple, compact, all fibre, and fully tunable optical comb generator to find application in DWDM systems. Deployed systems may require comb spacings of 50 GHz or 100 GHz. LiNbO$_3$ modulators have been reported with modulation bandwidths of up to 100 GHz [9] which would enable our system to be fully compatible with ITU recommended WDM channel spacings [10].