Mode-Locked Semiconductor Lasers: from Giga-Hertz to Tera-Hertz

John H. Marsh and Lianping Hou
School of Engineering
University of Glasgow
Glasgow G12 8QQ, United Kingdom
john.marsh@glasgow.ac.uk

Abstract— Mode-locked lasers operating at 1.5 microns are described, in particular the evolution in the laser design as the mode-locked frequency is increased from ~10 GHz to 1.4 THz. Novel DBR constructions and nonlinear conversion are required to reach the highest frequencies.

Keywords—Semiconductor laser; mode-locking; integrated optics; THz generation; DBR laser

I. INTRODUCTION

Mode-locking is a useful technique for generating short optical pulses at high repetition frequencies. In mode-locking, longitudinal modes of the laser are locked in phase, phase locking being achieved at the fundamental round trip frequency of the cavity by placing a saturable absorber (SA) adjacent to one facet. The laser then produces a series of pulses whose period is that of the cavity round trip time. Because of their small size and short cavity length (typically 0.5 mm to 10 mm), edge-emitting semiconductor lasers have fundamental mode-locking frequencies in the range from ~4 to ~80 GHz. A variety of techniques can be used to force the laser to mode-lock at a harmonic of this frequency. Here we discuss the evolution in device and material design as the mode-locking frequency is increased from ~10 GHz to > 1 THz for lasers operating at 1.5 μm .

II. MATERIAL AND LASER DESIGN

A. Epitaxial Structure

The ideal mode-locked laser emits short pulses with a high peak power. These two requirements conflict in terms of the epitaxial design, as designs with a high gain coefficient will also exhibit high nonlinearities. Lasers operating at 1.5 μm present particular challenges as the gain coefficient is lower, and optical nonlinearities higher, than in comparable short wavelength (850 – 980 nm) devices. Our solution is to utilize a low gain structure, giving in a small nonlinearity, in a long cavity configuration, to deliver high power.

B. Colliding pulse mode-locking (CPM)

Several techniques can be used to force the device to operate at a harmonic of the fundamental frequency. In colliding pulse mode-locking (CPM) one or more SAs are placed at strategic points in the cavity, rather than adjacent to one of the facets as in fundamental frequency mode-locking.

Several pulses circulate in the cavity and interfere (collide) in the SAs. For example, a single SA placed in the centre of a cavity will favour mode-locking at the 2nd harmonic. We have used this technique up to 240 GHz at 1.5 μm . Although this is an excellent approach for reaching modest harmonic numbers, it is difficult in practice to design CPM lasers to mode-lock at harmonics higher than ~10.

C. Coupled cavity mode-locking (CCM)

In coupled cavity mode-locking (CCM), a short cavity is created within the laser and is coupled into a longer cavity such that the ratio of the cavity lengths is an integer. The shorter cavity determines the mode-locking frequency while the longer cavity provides the gain required for stable operation and contains the SA. The highest reported mode-locking frequency of 2.1 GHz was achieved in an 860 nm CCM laser operating at the 33rd harmonic [1]. We have demonstrated this technique up to 640 GHz at 1.5 μm , a frequency ultimately limited by the finesse of the short cavity. CCM devices can be difficult to manufacture as the fabrication process generally depends critically on cleaving to precision tolerances.

D. Sampled DBR Grating mode-locking (SGDM)

In order to circumvent the disadvantages of CPM and CCM lasers, we have recently proposed the use of sampled grating distributed Bragg reflector (DBR) structures for reaching THz repetition frequencies [2]. The sampled-grating DBR provides strong frequency selectivity at the mode-locked frequency while the ‘soft walls’ of the reflectors relax fabrication tolerances and ensure the long cavity can self-adjust to supporting an integral number of mode-locked periods. Devices at 1.5 μm provide nearly transform-limited pulse trains at 640 GHz and 1.28 THz with a high degree of controllability. Our most recent results use sampled gratings of 2 different periods and a sum frequency as high as 1.34 THz has been obtained through frequency mixing in the device.

References

- [1] D. A. Yanson, et al., ‘Ultrafast harmonic mode locking of monolithic compound cavity laser diodes incorporating photonic bandgap reflectors’, *IEEE Journal of Quantum Electronics*, **38**, pp1-11, Jan 2002
- [2] L. Hou; M. Haji, J. H. Marsh, ‘Mode locking at terahertz frequencies using a distributed Bragg reflector laser with a sampled grating’, *Optics Letters*, Vol. 38 Issue 7, pp.1113-1115 (2013)