Abstract — Compact solid-state lasers are an attractive potential source for high speed, low noise optical pulses suitable for microwave photonic systems such as optical A/D conversion or digital communications. These small devices can be mode-locked at the fundamental cavity resonance, thereby avoiding the complications arising from the presence of supermodes in harmonically mode-locked lasers. An Nd:YVO₄/MgO:LiNbO₃ microchip laser was mode-locked at a fundamental frequency of 20 GHz. When locked to a synthesizer, the phase noise was source-limited to -72 dBc/Hz at 1 kHz offset. A coupled optoelectronic oscillator structure was then used to mode-lock the device without a microwave source, yielding a further reduced phase noise of -95 dBc/Hz at 1 kHz offset.

Index Terms — Mode locked laser, analog-digital conversion, optical communication, solid lasers, electrooptic devices, timing jitter.

I. INTRODUCTION

For high bandwidth digital or analog/digital mixed signal systems, there are applications where photonic replacement of electronic components is desirable. New digital microwave photonic sub-systems (such as optical ADCs) require stable, rapid optical pulses for samplers or clocks. In these scenarios, mode-locking is the architecture of choice.

Much literature has recently been presented on the design and application of mode-locked EDFA ring lasers as a higher quality alternative to semiconductor lasers. This technology is well-established and highly modular in nature. However, their high number of components, cost, and large footprints make fiber lasers impractical for many applications. More importantly, their long lengths translate into low cavity resonances, usually in the MHz range. For rapid pulse rates, these lasers must be mode-locked at a high harmonic of the fundamental resonance. This harmonic mode-locking can generate supermode noise spurs. Although suppression schemes have been investigated [1], such methods require even more components.

In contrast to harmonic mode-locking, fundamental mode-locking of solid-state lasers is relatively less studied for microwave photonic applications (due to factors such as the difficulty realizing a suitable laser), yet is immune to supermode noise. For low noise, high bandwidth operation, it is thus essential that fundamental mode-locking be fully explored. This is the emphasis of the work presented here.

II. FUNDAMENTAL VS. HARMONIC MODE-LOCKING

Fundamental mode-locking is typically established by modulating either the optical loss or phase inside a laser with an electronic oscillator close to the cavity resonance. This leads to a pulsed optical output at a rate equal to this resonance frequency. In order to achieve the picosecond pulse rates desirable for high speed sampling, the laser cavity resonance frequency must be in the microwave range. For solid-state lasers, this translates into millimeter-scale devices.

Such a scale is impractical for fiber lasers. Instead, they are harmonically mode-locked to generate high speed optical pulses. However, harmonic mode-locking can also support multiple supermodes inside the cavity. These supermodes are not correlated, and the noises of neighboring wavelengths belonging to differing supermodes do not completely cancel at the photodetector. This is observed as noise spurs at offset frequencies corresponding to the harmonics.

In practice, the phase noise of mode-locked pulses is usually dominated by the locking source. Since the timing jitter is the integral of the phase noise, low noise is important for stable pulses, and the integration limits of the phase noise are an essential consideration. From sampling theory, it is reasonable to require low phase noise at frequencies up to the Nyquist (i.e., half the pulse repetition) frequency to fully exploit the bandwidth. For pulse rates at tens of GHz, this means that phase noise is still important at offset frequencies where harmonically mode-locked lasers can particularly suffer from thousands of spurs which will be cumulatively incorporated as additional timing jitter.

Fundamental mode-locking of solid-state lasers is a desirable alternative for high sampling rates. However, due to the typically shorter cavity lengths, there are several issues which must be considered that are not present (or have reduced importance) in lasers employing harmonic mode-locking. These include:

- Modal competition effects in short-cavity lasers
- Optimization of microwave/optical wave interaction
An important sacrifice when switching from harmonic to fundamental mode-locking is the loss of the ability to easily add more components inside the laser to alter functionality at any given time. As a result, though lasers which employ fundamental mode-locking may appear to have deceptively simple structures, functional considerations must be accounted for in their entirety before device assembly.

III. LASER DESIGN FOR FUNDAMENTAL MODE-LOCKING

A. Laser Configuration

A set of experiments were devised to investigate the suitability of fundamental mode-locking in a composite-cavity solid-state laser for microwave photonic applications. An Nd:YVO₄/MgO:LiNbO₃ electro-optic microchip laser was selected in order to achieve high optical spectral quality at 1.06 μm while maintaining a small form factor [2]. These materials are commonly available, and are no more difficult to assemble (or mass produce) than the common green laser pointer. Since fundamental mode-locking is generally impractical at microwave frequencies inside a ring architecture, a Fabry-Perot structure was employed. The use of discrete gain and modulator crystals also allowed a degree of modularization by offering the possibility of moving to different operating wavelengths (e.g., 1.34 or 1.55 μm) by simply switching crystals.

The intracavity lithium niobate phase modulator had a length of approximately 1.75 mm, while the vanadate gain section had a length of 0.5 mm. Dielectric coatings were deposited on all optical surfaces, with 98% reflectivity on the far surface of the modulator and antireflection coatings on the others. A glass mirror with a high reflectivity to the lasing wavelength (1064 nm) and low reflectivity to the pump wavelength (808 nm) was used to complete the optical cavity. The distance between the two optical mirrors was adjusted to create a laser cavity with a free spectral range near 20 GHz. The input pump beam was provided by a narrow-stripe laser diode, using free space coupling optics to minimize the beam waist inside the gain crystal in order to enforce single transverse mode operation.

B. Modal Competition Effects in Short-Cavity Lasers

In general, mode-locked lasers require an electronic oscillator as a locking source to establish the pulsing behavior. An elegant method of circumventing the need for a high frequency oscillator is the regenerative mode-locking scheme, first demonstrated in 1968 [3]. A novel improvement to this feedback which is attractive for microwave photonics was suggested by Yao and Maleki in [4]. In this architecture, which is known as coupled optoelectronic oscillation (COEO), a long fiber delay is added to the regenerative feedback loop to increase the effective quality factor (Q) and reduce the phase noise.

Using a Fabry-Perot architecture with a homogeneously broadened gain material (such as Nd:YVO₄) reduces the potential number of free-running lasing modes. This makes the predictability of the optical behavior (especially modal competition) an important consideration for regenerative mode-locking. Therefore, spatial hole burning effects were investigated to ensure that a laser cavity designed to have a free spectral range of 20 GHz did in fact have multimode operation of adjacent cavity modes. This is needed to yield the free-running microwave signal at the fundamental cavity resonance necessary for feedback.

![Fig. 1. Conceptual diagrams of modal competition issues in homogeneously broadened materials. Spectra on left represent the free-running optical signals; spectra on right are the detected microwaves. Cases (a) and (b) are discussed below.](image-url)
C. Optimization of Microwave/Optical Wave Interaction

The electronic locking signal was coupled to the laser phase modulator through the use of a microwave waveguide. As stated previously, sensitivity of the mode-locked laser to the microwave signal was a primary concern, given the short interaction length. Therefore, simulations were conducted (using HFSS) to optimize the microwave coupling. These simulations focused on maximizing the electric field inside the phase modulator section, and neglected the presence of the glass mirror and gain medium (due to the significantly higher dielectric constant of the phase modulator with respect to these elements), as well as the presence of small waveguide apertures (which allowed optical beams to enter and exit the microwave waveguide).

As determined from the simulations (see Fig. 2), coupling was facilitated by the use of a circular post (to concentrate the electric field inside the phase modulator) and a waveguide short (to create a microwave cavity to further increase the field amplitude inside the modulator). A waveguide isolator was included to prevent back reflections from re-entering the microwave chain. Fig. 3 is a cross-section conceptually illustrating the mechanism enabling the microwave/optical wave interaction.

IV. EXPERIMENTAL RESULTS

First, the laser was mode-locked by using an Anritsu 69637B microwave synthesizer set at 20 GHz. A block diagram of the experimental setup is shown in Fig. 4.


The optical spectrum of the free-running and mode-locked laser is shown in Fig. 5.

![Fig. 5. (a) Free-running, and (b) mode-locked optical spectrum](image)
The optical pulses were detected with a high speed photodetector, and the phase noise of the resulting microwave signal was found to be -72 dBc/Hz at 1 kHz offset. The phase noise of the synthesizer was also measured for reference, and the spectra of both were similar, as expected in the source-limited case.

Next, the laser was mode-locked by using a coupled optoelectronic oscillator (COEO) structure, as shown in Fig. 6. In order to increase the Q of the regenerative loop, an optical fiber delay line was inserted between the laser and the photodetector. As a result, the output of the detector was a stable oscillation at 20 GHz (Fig. 7), with a phase noise of -95 dBc/Hz at 1 kHz offset, with no supermode spurs. This significantly exceeds the performance of typical high frequency synthesizers, and is suitable for microwave photonic applications.

Fig. 6. Block diagram of fundamental regenerative mode-locking experiment. Abbreviations – DELAY: fiber-optic delay line, WBF: wideband microwave filter, MDC: microwave directional coupler. All other abbreviations as in Fig. 4.

Fig. 7. Regeneratively mode-locked laser microwave beat frequency spectrum

V. CONCLUSION

For optimum performance of mode-locked lasers as samplers or clocks in next-generation microwave photonic systems, it is necessary to investigate the parameters which ensure high speed performance while maintaining good purity. Harmonically mode-locked lasers, such as fiber ring lasers, have been touted as easily-built candidates for achieving high pulse rates. However, low phase noise is an important metric, as the integral of the phase noise determines the timing jitter. For applications like sampling inside high-speed optical analog-to-digital converters, the phase noise at high offsets may need to be considered in the timing jitter. In these cases, supermode noise spurs induced by harmonic mode-locking can negatively affect the timing jitter, and it may be more advantageous to use fundamental mode-locking as a solution instead.

An Nd:YVO$_4$/MgO:LiNbO$_3$ electro-optic microchip laser was mode-locked at the designed fundamental cavity resonance frequency of 20 GHz. When locked to a synthesizer, the phase noise of the detected beat frequency was -72 dBc/Hz at 1 kHz offset. The laser was then regeneratively mode-locked in a coupled optoelectronic oscillator (COEO) architecture, with a phase noise of -95 dBc/Hz at 1 kHz offset and no supermode noise spurs at further offset frequencies. Thus, it appears that fundamental regenerative mode-locking of a compact solid-state laser is a promising candidate for developing applications such as all-optical A/D conversion.

The current performance of the electro-optic microchip laser is competitive with fiber laser-based COEOs [5]. Exceeding these results will require reduced cavity losses, increased modulation sensitivity, and system stabilization to increase the effective Q. Therefore, further research will be conducted in several areas. First, a study to suppress mode-pulling effects due to optical intracavity resonances by utilizing crystal wedging is currently underway. Next, a more detailed investigation of improved microwave coupling architectures exploiting microwave resonance effects is also in progress. Finally, a comprehensive analytical model of the COEO method applicable to short-cavity lasers will be pursued, with the goal of exploring this model to potentially realize further experimental improvement of the phase noise.

REFERENCES