Mode-Locked Chip Laser using Waveguide Arrays

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Abstract—We demonstrate theoretically that robust mode-locking can be achieved on a semiconductor chip with a waveguide array architecture. The waveguide arrays are used as an ideal saturable absorption mechanism for initial noise start-up as well as pulse shaping and stabilization. The cavity gain is provided by an injection current and forward biasing of the semiconductor material. The technology can be integrated directly with semiconductor architectures and technologies, thus allowing for the potential of an on-chip, broadband device.

Mode-locked lasers are an increasingly important technological innovation as their potential applications have grown significantly over the past decade. Indeed, this promising photonic technology has a wide number of applications ranging from military devices and precision medical surgery to optical interconnection networks, broadband sources, and optical clocks. In some cases, such technologies have placed a premium on the engineering and optimization of mode-locked laser cavities that are aimed at producing output pulses of tens to hundreds of femtoseconds with maximal peak powers and energies. Thus, the technological demand for novel techniques for producing and stabilizing ultra-short pulses has pushed mode-locked lasers, in particular fiber-based laser designs, to the forefront of commercially viable, nonlinear photonic devices. Although fiber offers an attractive technological approach to mode-locking, it is envisioned that chip-based devices could play a significant role if robust mode-locking can be demonstrated on-chip. Here, we advocate the use of waveguide arrays for a chip-based mode-locked laser design and demonstrate that robust mode-locking can be achieved using the effective saturable absorption generated by the waveguides.

Optical waveguide arrays (WGAs) have been demonstrated to have a wide range of potential photonic applications (1) including as the basis for all-optical signal processing (route and switching) in fiber optic networks and devices (2)–(6) and as potential saturable absorption mechanisms in mode-locked lasers (7)–(10). Indeed, with the advent of optical waveguide arrays, a new method exists to generate robust, mode-locked pulses by using the ideal saturable absorption behavior of the WGA (16). Here the aim is to demonstrate that mode-locking can be achieved on a chip-based design, thus circumventing the need for fiber and/or other external cavity components. Figure 1 demonstrates the envisioned experimental setup of a chip based mode-locked laser cavity. Unlike previous studies of fiber-based passive WGA mode-locking (7), (8), (16), the idea here is to use current injection and forward biasing of the semiconductor material to produce the requisite gain for mode-locking. Thus the all-chip cavity configuration envisioned takes advantage of several key physical effects for generating stable mode-locking.

Semiconductor WGA lasers have been well studied by Rahman and Winful (12) and others (11) in the context of continuous wave operation. Here, our aim will be to consider pulsed (mode-locked) operation of the cavity. Thus additional modeling terms will be required in the governing equations previously proposed (11), (12). The governing equations for the propagation of an electromagnetic field in a semiconductor material arises from a combination of a modal field expansion and a high frequency asymptotic reduction of Maxwell’s equations (11), (12). The evolution of the normalized electric field amplitudes in the waveguides $A_j$ and normalized carrier density in the first waveguide $V$ are given by

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\begin{align*}
\frac{\partial A_1}{\partial z} &= i(k_{11}A_1 + k_{12}A_2) - i\frac{\beta^2}{2} \frac{\partial^2 A_1}{\partial t^2} + i\gamma |A_1|^2 A_1 + i\sigma |A_1|^4 A_1 + \gamma A_1 (1 - iR) V (1 + \tau g \frac{\partial^2}{\partial t^2}) A_1 - \alpha_1 A_1 \\
\frac{\partial A_2}{\partial z} &= i(k_{12}a_1 + k_{22}A_2 + k_{32}A_3) - \alpha_2 A_2 \\
\frac{\partial A_3}{\partial z} &= i(k_{23}A_2 + k_{33}A_3) - \alpha_3 A_3 \\
\frac{dV}{dz} &= \frac{1}{T}(P_t - (\xi_1 + 2\gamma_1 V)|A_1|^2 - (1 + \delta_1)V)
\end{align*}
\]

where $z$ is the normalized distance in the waveguide array.
as an attracting state of the system. The bottom panels demonstrate the electric field dynamics in the neighboring waveguides A experiences amplification from the current injection and forward biasing of the semi-conductor material. The top two panels demonstrate the cold cavity startup of the electric field in the first waveguide along with the carrier density dynamics. As with typical mode-locked laser cavities, the mode-locked state acts as an attracting state of the system. The bottom panels demonstrate the electric field dynamics in the neighboring waveguides A2 and A3 along with the energy equilibration in the first waveguide (\|A_1\|^2 = \int |A_1|^2dt).

and t is the normalized time. The parameter g represents the semiconductor gain strength which is determined by the current injection [11]. Note that gain is only applied to the first waveguide A1 as shown in Fig. 1. In the first equation, the parameters \(\beta''\), \(\gamma\), \(\sigma\), and \(\tau\) determine the chromatic dispersion, nonlinear self-phase modulation generated from the Kerr nonlinearity, the three-photon absorption coefficient [13], and the gain bandwidth in the semiconductor. As is standard with coupled mode-theory, the parameters \(k_{ij}\) measures the overlap of the modal structures from between waveguide i and j [14]. For the carrier density, the parameters \(R\), \(T\), \(\xi\), \(\gamma\), \(\delta\) are related to the time-response, size and specific semiconductor material used [11], [12].

For AlGaAs, for instance, many of the parameters can be explicitly characterized. For instance, it is known that the chromatic dispersion coefficient is 1.25 ps²/m, the nonlinear index is 3.6 m⁻¹W⁻¹ and that the three-photon absorption coefficient is approximately \(2 \times 10^{-5} m^{-1} W^{-2}\) [13]. However, many of the other coefficients depend largely on the waveguide separation and waveguide width, parameters that can be tailored and engineered for the mode-locking requirements here. Waveguide widths can be easily envisioned to be on the order of 1-5 microns with separations on the order of 2-10 microns. A driving current for the system would be somewhere in the tens of milliamps regime [11]. Given the large parameter space to be potentially explored, our computational studies will focus on simply demonstrating the concept and potential ability to construct such a mode-locked chip device. Clearly the choice of specific semiconductor material, its time constants, nonlinearity, and geometrical configuration give a great deal of flexibility in achieving the parameter regime necessary for mode-locking.

To demonstrate the mode-locking process, Eqs. (1) are simulated over a large number of round trips. From a cold cavity startup, i.e. an initial low-amplitude, white-noise electromagnetic field, the cavity quickly forms into a robust mode-locked pulse. Figure 2 demonstrates the mode-locking process for a white-noise initial condition. As is expected in a mode-locked cavity, the effective saturable absorption of the WGA quickly shapes the pulse into a robust mode-locked pulses while also stabilizing the cavity energy. The carrier density also takes on a robust temporal response during the mode-locking process. As with a fiber based device [8], the electric field in the neighboring waveguides A2 and A3 inherit their from A1. Indeed, both waveguides A2 and A3 experience a net loss. However, A1 continuously feeds energy into these waveguides, thus stabilizing the robust structures shown. The bottom right panel shows the equilibration of cavity energy during the mode-locking process. For this demonstration, the dimensionless parameters in Eqs. (1) are given by \(k_{11} = k_{22} = k_{33} = 0, k_{12} = k_{23} = 6, \beta'' = -1, \gamma = 20, \sigma = 0.1, \tau = 0.1, R = 3, T = 1, \xi_1 = 1, \gamma_1 = 1, \delta_1 = 0, \alpha_1 = \alpha_2 = 0, \alpha_3 = 10\). If \(v_1 > 0\), then \(g = 1\). If \(v_1 < 0\), then \(g = 0\).

As with all mode-locked lasers, the performance limits of single-pulse operation are typically always limited by gain bandwidth restrictions. Thus as the injection current is increased, single pulse operation as illustrated in Fig. 1 is destabilized and a multi-pulsing transition is exhibited. Such a phenomenon is generic for laser systems that are driven by the interplay of saturable gain and nonlinear losses [15]. This is also the case for the WGA chip laser. In particular, as the gain is increased through ramping up of the injection current, the single-pulse per round trip bifurcates the a two-pulses per round trip configuration. Figure 3 demonstrates this bifurcation process. The top two panels demonstrate the robust single- and double-pulse per round trip configurations that arise from
an initial noise startup. The bottom panels show the pulse energy for the entire cavity, i.e. the sum of all the pulses, along with the energy of each individual pulse during the bifurcation process from one to three pulses per round trip. On the one hand, the multi-pulsing instability is often deleterious as it limits the energy and power of single pulse operation. On the other hand, the behavior suggests that the chip laser is in keeping with the fundamental behavior of other mode-locking configurations, thus potentially allowing one to apply the intuition of cavity design to the chip laser.

In conclusion, we have demonstrated theoretically a proof-of-concept mode-locked chip laser. Thus robust, ultra-short pulse generation can be achieved on an all-chip device, potentially revolutionizing the use of mode-locked lasers in semiconductor architectures. The mode-locked chip laser is based upon proven WGA technology and its previously demonstrated saturable absorption properties in a fiber-based setting [16]. Given its technological promise, the chip laser is a promising advancement for integration into chip design and architecture. It only remains to pick appropriate semiconductor material and its geometrical configuration in order to access a parameter space where robust mode-locking occurs. The primary hurdle in achieving this physical regime is the typical time constants associated with the recovery of the carrier dynamics. However, longer cavities can be generated on chip (See Fig. 1). In practice, managing the cavity losses has been shown in practice to be very important in achieving mode-locking [16]. Moreover cavity design (waveguide width and spacing) along with an appropriate semiconductor material may be able to render this a robust and inexpensive mode-locking technology that can greatly impact semiconductor laser technologies.

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Fig. 3. Mode-locked chip dynamics as a function of increased injection current (gain) on waveguide $A_1$. The top left panel shows the single pulse per round trip configuration that is desirable whereas the top right panel shows the result of increasing the injection current, thus producing higher gain and two pulses per round trip. The bottom panels shows the cavity energy for the total cavity, $E_0$, (left bottom) and for each individual pulse, $E_p$ (right bottom).