Pulsewidth and Chirp of SOA-EAM Ring Mode-Locked Lasers

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Abstract Generation of high-quality short pulses at repetition rates in the GHz range is a key function for OTDM and WDM transmission and signal processing systems. In particular, active mode-locking can be used to produce stable and well synchronized ultrashort pulses suitable for such applications. In this paper, an analytical model of an actively mode-locked SOA-EAM ring laser is derived and used to predict the main parameters of the generated pulse train.

Keywords: Ultrashort pulse sources, Mode-locked lasers, ABCD matrices

1. Introduction

High-quality optical pulses in the sub-picosecond rage are essential for high-speed optical communication and all-optical signal processing systems. Short pulse sources for the 1.3 μm and 1.5 μm communication windows have extensively been investigated in the last two decades. They are of particularly importance for many applications, e.g. for optical sampling techniques [Shirane00], clock generation and recovery [Sartorius98; Lach96] and OTDM/OCDM/WDM transmitters [Aleksić01; Huang00].

Usually, an erbium-doped fiber amplifier (EDFA) is used for the amplification of circulating optical pulses in a mode-locked ring laser [Pfeiffer93; Ellis99; Bakhshi00]. Since erbium-doped fiber ring lasers (ED-FRLs) are usually tens of meters long, the cavity round-trip frequency, and thus, the mode spacing of such lasers is in the MHz range. For this reason, ED-FRLs have to be mode-locked at a very high harmonic of the fundamental ring frequency if repetition rates in the GHz range are required. This can cause instabilities in pulse generation, which are additionally enhanced by fluctuations of polarization states and environmental perturbations such as change in temperature and mechanical stress. By using a semiconductor optical amplifier (SOA) as a gain medium, total cavity length can be considerably shortened making possible a more stable operation compared with ED-FRLs, even at high repetition rates of 10 GHz [Guy96; Kim99] or 40 GHz [Zoiros00].

In this paper, an analytical model of an SOA-based ring laser is derived. The model is based on the ABCD matrix formalism and allows an efficient prediction of the main pulse parameters such as temporal width and time-bandwidth product.

2. ABCD Model of an SOA-based ring laser

The time-domain ABCD matrix method has been shown to be a very useful tool to determine pulse parameters such as pulsewidth and chirp of mode-locked fiber-ring lasers. It can be used to obtain an analytical steady-state solution using the Gaussian approximation. This method has been developed by Nakazawa [Nakazawa98], by adapting the spacial-domain model based on the Hermite-Gaussian beam, which has been used to analyze stable resonator modes in the laser cavity [Kogelink66; Siegman65; Boyd62; Fox61]. Recently, the time-domain model based on the ABCD law has been deployed to investigate pulse parameters of actively mode-locked lasers using both frequency and amplitude modulation [Nakazawa98; Zhang01; Li99; Poti01]. To take into account dispersion and nonlinear effects more accurately, the model can be extended by distributing the amplifier gain and fiber linear and nonlinear effects along the cavity and solving the steady-state equation numerically using an iterative algorithm [Poti01; Li99]. However, an analytical model has the advantage of better understanding the basic processes. It also enables a fast determining of the most important laser parameters. Therefore, we will here derive analytical expressions for pulsewidth and time-bandwidth product of an SOA-EAM ring mode-locked laser using the ABCD matrix method.

A linearly chirped Gaussian pulse is usually expressed as:

$$u(t) = \sqrt{P_0} \exp\left[-\frac{t^2}{2\tau_p^2}(1+iC)\right] \quad , \tag{1}$$

where P_0 is the peak power of the pulse, τ_p is the $1/e$ pulsewidth, and C denotes the dimensionless linear chirp parameter. In the time-domain ABCD matrix formalism, the q-parameter comprising the width and chirp of the Gaussian pulse that propagates through optical elements is defined as:

$$\frac{1}{q} = \frac{1}{\tau_p^2} - iC \quad . \tag{2}$$

The optical elements in the laser cavity such as amplifiers, filters, modulators, dispersion, and lumped SPM elements are characterized by ABCD matrices of the form:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \tag{3}$$

The determinants of all matrices must satisfy $AD - BC = 1$. When a Gaussian pulse passes through an optical element characterized by an ABCD matrix, the q-parameter at the output is:

$$q_{out} = \frac{Aq_{in} + B}{Cq_{in} + D} \quad . \tag{4}$$

In the case that several optical elements are cascaded, the matrices are easily multiplied, so the steady-state solution for a laser cavity of length L can be obtained by using the relationship $1/q(0) = 1/q(L) = 1/q$. Then, form Equation 4 one can obtain:

$$\frac{1}{q} = \frac{(D - A) \pm \sqrt{(A - D)^2 + 4BC}}{2B} \quad . \tag{5}$$

By choosing a solution of Equation 5 that satisfies $\mathrm{Re}\{1/q\} > 0$ (τ_p^2 is always positive) and introducing this solution in Equation 2, expressions for τ_p and C can be found.

The time-domain matrix formalisms of three basic optical elements determining short pulse generation in the SOA-based ring mode-locked laser configuration depicted in Figure 1 are summarized in Table 1. The derivation of these matrices are shown in the Appendix.

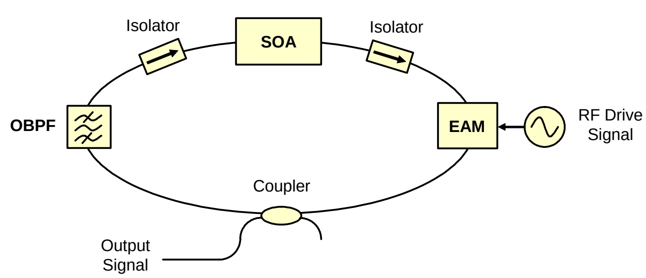

Figure 1. Schematic diagram of an SOA-based ring mode-locked laser configuration

Table 1. ABCD matrices of three basic optical elements

optical element	**ABCD matrix**	**parameters definition**
optical bandpass filter	$\begin{pmatrix} 1 & \frac{2\mu}{\Omega_f^2} \\ 0 & 1 \end{pmatrix}$	Ω_f: HWHM filter bandwidth μ: transmittivity of the filter
semiconductor optical amplifier	$\begin{pmatrix} 1 & \frac{2G_s}{\Omega_g^2} \\ 0 & 1 \end{pmatrix}$	G_s: saturated amplifier gain given by Equation 8 Ω_g: HWHM gain bandwidth
electro-absorption modulator (EAM)	$\begin{pmatrix} 1 & 0 \\ \frac{V_m}{V_0}(2\pi f_m)^2 & 1 \end{pmatrix}$	V_m: amplitude of the modulation voltage V_0: bias voltage where the extinction ratio of the modulated optical signal is $1/e$ f_m: modulation frequency

Now, we can obtain an analytical expression for width and time-bandwidth product of linearly chirped Gaussian pulses produced by a fiber ring mode-locked laser with an SOA and an electroabsorption modulator (EAM). The overall ABCD matrix of the laser is given by:

$$\begin{aligned} T_{MLL} &= T_{EAM} \cdot T_{OBPF} \cdot T_{SOA} \\ &= \begin{pmatrix} 1 & 0 \\ \frac{V_m}{V_0}(2\pi f_m)^2 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{2\mu}{\Omega_f^2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{2G_s}{\Omega_g^2} \\ 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 1 & b \\ m & mb+1 \end{pmatrix} = \begin{pmatrix} A_{MLL} & B_{MLL} \\ C_{MLL} & D_{MLL} \end{pmatrix} \quad , \end{aligned} \tag{6}$$

where

$$b = \frac{2G_s}{\Omega_g^2} + \frac{2\mu}{\Omega_f^2} \quad and \quad m = \frac{V_m}{V_0}(2\pi f_m)^2 \quad , \tag{7}$$

and

$$G_s = \exp\left[g_0 L \left(\frac{1-\exp(-T_R/\tau_s)}{1-\exp(-T_R/\tau_s)+\overline{P}/P_s}\right)\right] \quad . \tag{8}$$

In the above expression for G_s, g_0 represents the small-signal gain of the SOA, L is the amplifier length, τ_s is the carrier lifetime, $T_R = 1/f_m$ is the time period between two successive pulses, $\overline{P} = P_0\sqrt{\pi} f_m \tau_p$ is the average power of the Gaussian pulse train, and P_s is the saturation power. Thus, by introducing the matrix elements into Equation 5 the q parameter can be obtained as:

$$\frac{1}{q} = \frac{mb + \sqrt{(mb)^2 + 4mb}}{2b} = \frac{m\left(1+\sqrt{\frac{4}{mb}+1}\right)}{2} \quad . \tag{9}$$

Finally, the pulsewidth τ_p can be calculated from:

$$\tau_p = \sqrt{q} = \sqrt{\frac{2}{m\left(1+\sqrt{\frac{4}{mb}+1}\right)}} \quad . \tag{10}$$

The phase of the optical field at the output of the SOA, $\varphi_{out}(t)$, is given by [Agrawal89]:

$$\varphi_{out}(t) = \varphi_{in}(t) - \frac{\alpha}{2} h(t) \quad , \tag{11}$$

where $\varphi_{in}(t)$ is the optical phase at the input of the SOA, α is the linewidth enhancement factor, and $h(t)$ represents the integrated gain at each point of the pulse profile, i.e., $h(t) = \int_0^{L_c} g(z,t)dz$. The frequency chirp parameter can be estimated roughly at the pulse center ($t = t_0$) by:

$$\begin{aligned} C &= -\frac{\alpha}{2} \cdot g(t_0) \\ &= -\frac{\alpha}{2} \cdot g_0 L \left(\frac{1-\exp(-T_R/\tau_s)}{1-\exp(-T_R/\tau_s)+\overline{P}/(\sqrt{\pi} f_m \tau_p P_s)}\right) \quad . \end{aligned} \tag{12}$$

In Equation 12, $P_0 = \overline{P}/(\sqrt{\pi} f_m \tau_p)$ is the peak power of the linearly chirped Gaussian pulse. The time-bandwidth product of such a pulse is given by:

$$\Delta t \Delta \nu = \frac{2\ln(2)}{\pi}\sqrt{1+C^2} \quad . \tag{13}$$

Thus, by using Equations 13, 12, 10, 8, and 7, the pulsewidth and time-bandwidth product of a pulse train generated in the SOA-EAM mode-locked laser can be estimated.

3. Results and Discussions

Figure 2 shows the calculated pulsewidth versus modulation depth (V_m/V_0) for three different optical bandpass filters. The higher the modulation depth is, the shorter pulses can be generated. The pulsewidth is also influenced by the bandwidth of the OBPF inserted in the loop. Filters with larger bandwidths allow formation of shorter pulses. Optical pulses as short as 5.5 ps are possible by using an OBPF with 4 nm FWHM bandwidth.

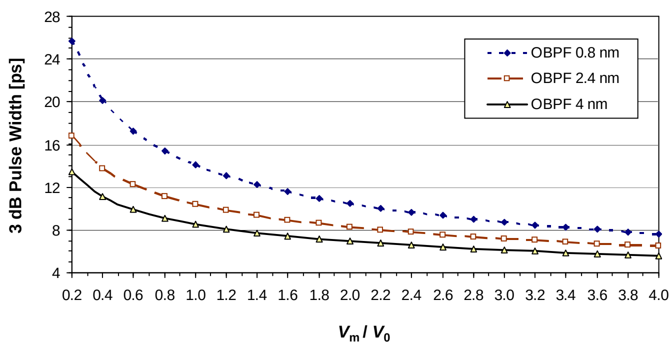

Figure 2. 3 dB pulsewidth vs. modulation depth V_m/V_0 ($f_m = 10$ GHz)

When the optical power level increases, the ratio $\overline{P}/P_s$ becomes larger. Consequently, the SOA saturates and the gain of the device is reduced. The stimulated carrier lifetime in the active region decreases, thereby increasing bandwidth of the device and enabling formation of shorter pulses. Figure 3 shows the dependance of the pulsewidth on the ratio $\overline{P}/P_s$ while driving the EAM with 1 GHz and 10 GHz electrical signal and using three different loop filters. It can be seen that quite short pulses can be obtained for $\overline{P}/P_s > -6$ dB (i.e., $\overline{P} > 0.25 \cdot P_s$) and filter bandwidths ≥ 4 nm. Note that the optical power in the loop must not be increased too much, because the SOA can not provide sufficient gain for lasing if it is deeply saturated. At a very high power level, the mode-locked laser may die out or become unstable.

The time-bandwidth product of the generated pulse train increases if the optical power level becomes lower. The dependencies of the time-bandwidth product on the ratio $\overline{P}/P_s$ for repetition rates of 1 GHz and 10 GHz are plotted in Figure 4. By using a 4 nm filter, $\Delta t \Delta \nu$ becomes larger than 1.0 for $\overline{P}/P_s < -8$ dB and $f_m = 1$ GHz. For optical powers larger than $0.63 \cdot P_s$ ($\overline{P}/P_s > -2$ dB) a time-bandwidth product of less than 0.5 can be achieved for $f_m = 10$ GHz.

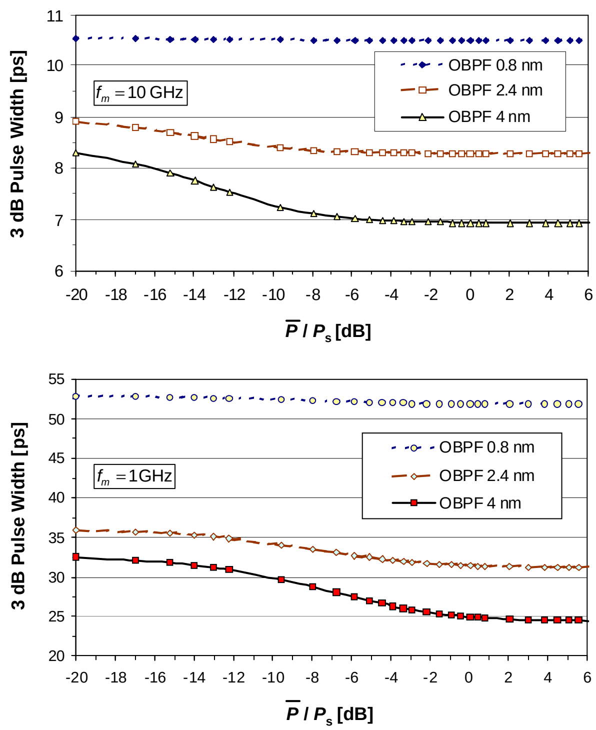

Figure 3. 3 dB pulsewidth vs. $\overline{P}/P_s$ ($V_m/V_0 = 2$)

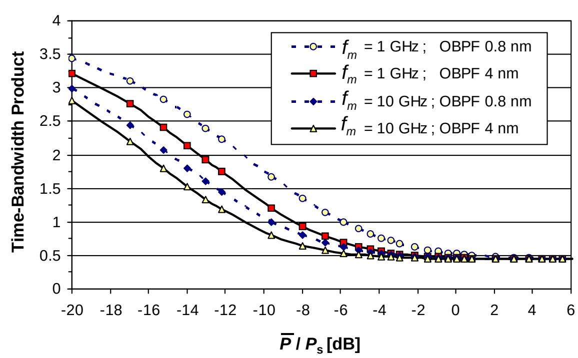

Figure 4. Time-bandwidth product vs. $\overline{P}/P_s$ ($V_m/V_0 = 2$, $\alpha = 3$)

Effects of small-signal gain on the pulse parameters are shown in Figures 5 and 6. A large gain will broaden the temporal width of the pulses, especially for lower optical powers and higher bandwidths of the loop filter. If the optical power at the input of the SOA is slightly lower than the SOA saturation power (for example for $\overline{P}/P_s = 0.8$), the pulsewidth remains low even for higher values of the small-signal gain.

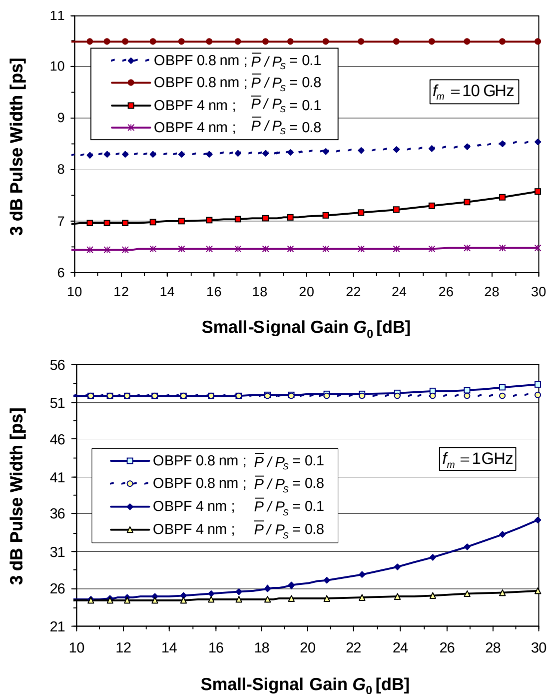

Figure 5. 3 dB pulsewidth vs. small-signal gain G_0 ($V_m/V_0 = 2$)

The larger the small-signal gain is, the larger the carrier density induced change of the gain and the refractive index in the SOA. That is, a large small-signal gain leads to a large red shift in frequency (shift to the lower frequencies), which broadens the spectrum of the amplified signal. Thus, the time-bandwidth product is increased because both spectral width and temporal width of the pulse train are increased. This effect is especially noticeable for lower power levels (e.g. for $\overline{P}/P_s = 0.1$) as it can be observed from Figure 6. If the optical power at the SOA input is increased to a value slightly lower than the saturation power, the amplifier gain is reduced, and consequently, the time-bandwidth product is decreased. For example, if $\overline{P}/P_s$ is set to 0.8, the time-bandwidth product remains low even for large gain values ($g_0 = 30$ dB).

The analytical model of SOA-based MLLs derived here can be used to predict the main laser parameters such as pulsewidth and chirp. Although this model is quite simple, it allows a sufficiently accurate prediction of the main laser parameters under steady-state conditions. For example, by setting the gain of SOA to 20 dB, the bandwidth of the loop filter to 1.2 nm, the linewidth enhancement factor to 4.0, the EAM modulation depth to $V_m/V_0 = 0.365$, and the ratio $\overline{P}/P_s$ to 0.4, one can calculate a pulsewidth of 18.4 ps and a time-bandwidth product of 0.69. This is in a very good agreement with the experimental results reported in [Kim99].

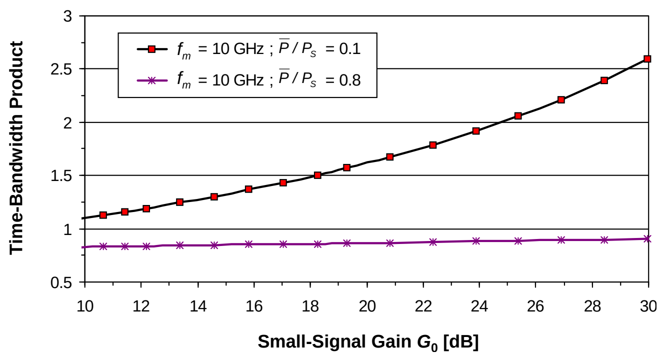

Figure 6. Time-bandwidth product vs. small-signal gain G_0 ($V_m/V_0 = 2$, $\alpha = 3$)

4. Summary and Conclusions

In conclusion, an analytical model for determining the pulsewidth and time-bandwidth product of a mode-locked fiber ring laser consisting of a semiconductor amplifier, an electroabsorption modulator, and an optical bandpass filter has been derived. This model predicts generation of Gaussian pulses as short as 5.5 ps with a time-bandwidth product of 0.46 by setting the modulation depth to 4 and using a 4 nm filter. The influence of the modulation depth, optical power level in the loop, and small-signal gain on the pulse parameters has been investigated. The results have shown that shorter pulses can be obtained for larger modulation depths and higher filter bandwidths, while an increase in small-signal gain causes a broadening of both the temporal and the spectral width of the generated pulse train. By adjusting the optical power level in the loop to $0.8 \cdot P_s$, where P_s is the SOA saturation power, the pulsewidth and time-bandwidth product increase only slightly when small-signal gain is increased.

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Appendix

In this Appendix, ABCD matrices for an electroabsorption modulator (EAM), an optical bandpass filter (OBPF), and a semiconductor optical amplifier (SOA) are derived.

Electroabsorption Modulator (EAM)

Modulation characteristics of an EAM can be expressed by its transmission function as follows [Oshiba98]:

$$T_{EAM} = \exp\left(-\left(\frac{V(t)}{V_0}\right)^{r_m}\right) \quad , \tag{A.1}$$

where $V(t)$ represents the reversed modulation voltage. The parameters r_m and V_0 determine the modulation efficiency. V_0 is defined as the bias voltage where the extinction ratio of the modulated optical signal is $1/e$. The technological parameter r_m is close to one for most bulk modulators, so we can neglect it in the following derivations. The modulation voltage of a sinusoidal drive signal is expressed by:

$$V(t) = V_b + V_m \cos(2\pi f_m t) \quad , \tag{A.2}$$

where V_b is the bias voltage, f_m is the modulation frequency, and V_m is the amplitude of the modulation voltage. Using the approximation $\cos(2\pi f_m t) \cong 1 - \frac{1}{2}(2\pi f_m)^2 t^2$ and Equations 1 and A.2 one can obtain:

$$\begin{aligned} u_{EAM}(t) &= u(t) \cdot T_{EAM} \\ &= \sqrt{P_0} \exp\left(-\frac{t^2}{2\tau_p^2}(1+iC)\right) \exp\left(-\frac{V_b + V_m \cos(2\pi f_m t)}{V_0}\right) \\ &\cong \sqrt{P_0} \exp\left(-\frac{V_b + V_m}{V_0}\right) \exp\left(-\frac{t^2}{2\tau_p^2}(1+iC) - \frac{V_m}{2V_0}(2\pi f_m)^2 t^2\right) \end{aligned} \tag{A.3}$$

Thus, the q parameter at the output of EAM can be expressed by:

$$\frac{1}{q_{out}} = \frac{1}{\tau_p^2} - iC + \frac{V_m}{V_0}(2\pi f_m)^2 \quad , \tag{A.4}$$

and finally, the ABCD matrix of an EAM can be written as:

$$\begin{pmatrix} 1 & 0 \\ \frac{V_m}{V_0}(2\pi f_m)^2 & 1 \end{pmatrix} \tag{A.5}$$

Optical Bandpass Filter (OBPF)

A parabolically approximated optical bandpass filter satisfies following equation:

$$\frac{\partial u}{\partial z} = \frac{\mu}{\Omega_f^2} \frac{\partial^2 u}{\partial t^2} \quad . \tag{A.6}$$

Here, μ represents the transmittivity of the filter at the center frequency f_c and Ω_f is the half width at half maximum (HWHM) filter bandwidth. The ABCD matrix is then given by:

$$\begin{pmatrix} 1 & \frac{2\mu}{\Omega_f^2} \\ 0 & 1 \end{pmatrix} \tag{A.7}$$

Semiconductor Optical Amplifier

Optical amplifier is an active element represented by its gain and gain bandwidth. The same matrix used for an optical bandpass filter can also be used for an amplifier while replacing filter transmittivity by amplifier gain coefficient, g, and filter bandwidth by gain bandwidth, Ω_g.

The saturated gain of a semiconductor optical amplifier (SOA) is given by $G_s = \exp(g_s L) = \exp[g_0 L/(1 + \overline{P}/P_s)]$, where P_S is the saturation power given by $P_s = A_{eff} h\nu/(\Gamma a \tau_s)$, $\overline{P}$ is the average input power, and g_0 is the small-signal gain. For pulsewidths much smaller than the carrier lifetime τ_s, i.e., if the input pulses are shorter than 50 ps, the amplifier gain has no time to recover in pulse duration. It recovers from its saturated value g_s to a higher value g_r in the time period between two pulses ($T_R = 1/f_m$). The recovery of the gain can be estimated by [Peng02]:

$$g_r = (g_s - g_0) \exp\left(-\frac{T_R}{\tau_s} \right) + g_0 \quad . \tag{A.8}$$

When the pulse repetition rate is high, the gain of the SOA can not recover completely in the time between two successive pulses. Therefore, the pulses experience a gain lower than the small-signal gain. Thus, the saturated gain of the SOA for a pulse train with high repetition rate and high power can be expressed as:

$$g_s = \frac{g_r}{1 + \overline{P}/P_s} = g_0 \frac{1 - \exp(-T_R/\tau_s)}{1 - \exp(-T_R/\tau_s) + \overline{P}/P_s} \quad . \tag{A.9}$$

Thus, the ABCD matrix of an SOA is given by:

$$\begin{pmatrix} 1 & \frac{2}{\Omega_g^2} \exp(g_s L) \\ 0 & 1 \end{pmatrix} \tag{A.10}$$

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