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A comprehensive study on the phase noise characteristics of a single-mode fiber grating Fabry–Perot (FGFP) laser was conducted numerically. Adding to previous studies, the effects of external optical feedback (OFB), external cavity length, temperature, injection current, cavity volume, nonlinear gain compression factor and fiber grating parameters on phase noise characteristics are presented. The temperature dependence (TD) of phase noise was calculated according to the TD of laser parameters and not by the well-known Parkove equation. The frequency spectra of FGFP laser phase noise were calculated by using a Fourier transform. Results show that the TD of the phase noise in FGFP lasers is smaller than that for distributed feedback lasers. The shortest external cavity length that provides the minimum phase noise is found to be around 3.1 cm. In addition, the relaxation oscillation frequency shifts towards more than 6 GHz, which provides larger flat frequency range. Furthermore, phase noise can be eliminated either by increasing the injection current or the OFB level.

Keywords: fiber Bragg grating; numerical simulation; phase noise; rate equation; semiconductor laser

1. Introduction

Future access networks will have to meet the ever-increasing demand for large capacity. Wavelength division multiplexing passive optical networks (WDM-PONs) are an attractive option due to their high capacity, easy management, reliable network security, protocol transparency and upgradability. They are a potential system for the provision of broadband access for next-generation networks [1–5]. In practical implementation of WDM-PONs, a laser source with very high wavelength stability, minimum wavelength variation due to temperature and low static and dynamic chirp, which can be used at reasonably low cost, is indispensable [6–22]. Generally, distributed feedback laser diodes (DFB-LDs) are used in the WDM networks. However, the emission wavelength of a DFB-LD is highly temperature and injection current dependent, which is required to be accurately controlled. In addition, under long-term operation, higher injection current is necessary when laser aging effects start to surface, which might cause wavelength drift due to the injection current dependence of a DFB laser [6–9,11,13,14].

In recent years, the fiber grating Fabry–Perot (FGFP) laser, which can generate light with a highly stable wavelength, has been proposed as an alternative light source for WDM systems [6–16]. The FGFP laser is less sensitive to temperature variation compared to the conventional DFB-LDs. This is because the emission wavelength of a FGFP laser depends only on the Bragg wavelength of the fiber grating (FG), where its reflection peak experiences a wavelength drift against temperature at a rate of about 0.01 nm/°C, which is about 10 times less than the conventional DFB-LDs [8,9,13–16]. In addition, precise adjustment of the Bragg wavelength in a FG is easily achievable as compared to the emission wavelength of DFB lasers. Therefore, the FGFP laser is a promising candidate for the light source of a future dense WDM system [1–16]. However, FGFP laser output experiences phase fluctuations due to the quantum nature of light [17–21]. In addition, temperature variation causes fluctuation in the gain spectrum, threshold current and other cavity parameters [14–16,22,23]. Furthermore, external optical feedback (OFB) significantly affects the performance of semiconductor laser diodes (SLDs), which may fluctuate the light intensity and vary the dynamical and spectral behaviors of the laser. These will produce unwanted effect such as mode hopping and/or the ‘coherence collapse’, which makes the study of characteristics of SLDs with OFB essential [24–29].

The phase noise is of interest in evaluating the performance of coherent optical systems and optical fiber sensors [30–33]. Phase noise, associated with fluctuations in laser frequency, can be described as an additional amplitude noise occurring when the laser
beam is divided and then returned after a specified relative time delay [34–36]. Phase noise may result in linewidth broadening that leads to dispersion penalties, especially in long-distance optical links. Analysis of the phase noise is necessary for further improvement of device and system performance [30–36]. The effect of phase noise on performance of SLDs has been theoretically and experimentally reported [34–37]. However, only few studies have been reported on characteristics of phase noise considering the effect of OFB [35]. In addition, to the best of our knowledge, the effect of temperature on characteristics of phase noise when OFB is implemented with a FGFP laser has not yet been reported. Instead, in all previous reports, the temperature is assumed to be constant. In this paper, the phase noise characteristics of a FGFP laser is comprehensively investigated by considering the impact of OFB, temperature, injection current, gain compression factor, cavity volume and FG parameters.

2. Theoretical model

The FGFP model consists of three main sections, as shown in Figure 1. The first section is the Fabry–Perot (FP) laser with a length of \(L_d\). It is assumed that the reflection coefficient of the chip front facet is zero \(R_f \approx 0\), while the rear facet has a finite reflection coefficient of \(R_f\). The second section is a fiber with a length of \(L_{ext}\) and the third is the fiber Bragg grating (FBG) with reflection coefficient of \(r_{FBG}\).

The round-trip times of photons inside the internal and the external cavity are \(\tau_d = \frac{2n_dL_d}{c}\) and \(\tau_e = 2L_{ext}n_{ext}/c\), respectively, where \(c = 3 \times 10^8\) cm/s is the velocity of light in a vacuum, \(n_d\) is the group refractive index of the FP laser diode and \(n_{ext}\) is the fiber refractive index. According to an analysis of the simple external cavity model based on the arrangement in Figures 1(a) and 1(c), the effective reflection coefficient \(R_{eff}\) at \(z = L_d\) is given by [38,39]

\[
R_{eff} = \frac{R_f^2 + R_{OFB}^2 + 2R_fR_{OFB}\cos(\omega \tau_e)}{1 + R_f^2R_{OFB}^2 + 2R_fR_{OFB}\cos(\omega \tau_e)},
\]

where \(\omega \tau_e\) is the phase of the reflected light that travels through the external cavity and \(\omega\) is the laser angular frequency. In Equation (1), \(R_{OFB} = C_oR_{ext}\) is the amount of optical feedback reflection coupled into the FP laser diode, where \(C_o\) is the amplitude coupling coefficient between the FP laser diode and the grating fiber and \(R_{ext}\) is the power reflectivity of the FG defined as [40]

\[
R_{ext} = |r_{FBG}|^2 = \frac{(kL_{FG})^2 \sinh^2(qL_{FG})}{(\Delta \beta L_{FG})^2 \sinh^2(qL_{FG}) + (qL_{FG})^2 \cosh^2(qL_{FG})} \quad \text{if} \quad (kL_{FG})^2(\Delta \beta L_{FG})^2 \quad \text{if} \quad (kL_{FG})^2(\Delta \beta L_{FG})^2
\]

where \(L_{FG}\) is the grating length, \(\Delta \beta\) is the wavelength detuning, \(k\) is the coupling strength, \(q = \sqrt{k^2 - \Delta \beta^2}\) and \(\Omega = iq = \sqrt{\Delta \beta^2 - k^2}\).

The equation for threshold current of the FGFP laser [41], by considering the effect of temperature \((T)\) and the optical feedback (OFB), can be defined as

\[
I_{th,OFB}(T) = eVN_{th,OFB}(T)\times [A_{nr} + BN_{th,OFB}(T) + CN_{th,OFB}^2(T)],
\]

where \(e\) is the electronic charge, \(V\) is the volume of the active region, \(B\) is the radiative recombination coefficient, \(C\) is the Anger process and \(A_{nr}\) describes the nonradiative recombination rate. The \(N_{th,OFB}\) in Equation (3) is the well-known carrier density at the threshold condition [41], which by considering the effect of temperature and OFB can be defined as:

\[
N_{th,OFB}(T) = N_t(T) + \frac{1}{\Gamma v_a(T) \tau_{p,OFB}(T)},
\]

where \(N_t(T), a(T)\) and \(\tau_{p,OFB}(T)\) are the temperature-dependent parameters, known as transparency carrier density, gain coefficient and photon lifetime.
(with the OFB effect), respectively, \( \Gamma \) denotes the confinement factor and \( v_g = (e/\hbar) \) is the group velocity. The temperature-dependent parameters can be defined as [14]

\[
X(T) = X_o + \frac{\partial X}{\partial T}(T - T_o),
\]

where \( X_o \) is the initial value found at the reference temperature \( (T_o) \), which in this study is considered as the room temperature \( (25^\circ C) \). Since the OFB only affects the photon lifetime in Equation (4), \( \tau_{p, \text{OFB}}(T) \) can be modeled as

\[
\tau_{p, \text{OFB}}(T) = \frac{1}{v_g \alpha_{\text{tot, OFB}}(T)},
\]

where \( \alpha_{\text{tot, OFB}}(T) \) is the total loss of laser cavity defined as [41,42]

\[
\alpha_{\text{tot, OFB}}(T) = \alpha_{\text{int}}(T) + \frac{1}{2L_d} \ln \left( \frac{1}{R_L R_{\text{eff}}} \right),
\]

where \( \alpha_{\text{int}}(T) \) is the temperature-dependent internal cavity loss and \((1/2L_d)(\ln(1/R_{\text{eff}}))\) is the mirror loss. Finally, \( N_{\text{th, OFB}} \) can be expressed as:

\[
N_{\text{th, OFB}}(T) = N(t) + \frac{\alpha_{\text{int}}(T) + \frac{1}{2L_d} \ln \left( \frac{1}{R_L R_{\text{eff}}} \right) + \frac{1}{2L_d} \ln \left( \frac{1}{R_{\text{eff}}} \right)}{\Gamma (T)}.
\]

Equation (8) gives the general expression for threshold carrier density that is used to calculate the net rate of stimulated emission in the active region.

### 3. Phase noise characteristics

By considering the effect of temperature and OFB described in the previous section, the phase noise characteristics of a FGFP laser can be derived from the well-known coupled rate equations [42], after taking into account the effect of OFB and temperature variation. In this case, different noise sources, \( F_i(t) \), including the carrier number, \( N(t) \), photon number, \( S(t) \), and the optical phase, \( \phi(t) \), can be described in this expression as:

\[
\frac{dN(t)}{dt} = \frac{I(t)}{q} - \frac{N(t)}{\tau_{c, \text{OFB}}} - g \frac{N(t) - N_o}{1 + \varepsilon S(t)} S(t) + F_N(t),
\]

\[
\frac{dS(t)}{dt} = g \frac{N(t) - N_o}{1 + \varepsilon S(t)} S(t) - \frac{S(t)}{\tau_{p, \text{OFB}}} + R_{sp, \text{OFB}} + F_p(t),
\]

\[
\frac{d\phi(t)}{dt} = \frac{1}{2} \alpha G_N(N(t) - \tilde{N}) + \frac{\arg(R_{\text{ext}})}{\tau_d} + F_{\phi}(t),
\]

where \( I(t) \) is the injected current, \( \tau_{c, \text{OFB}} = (\epsilon VN_{\text{th, OFB}}/I_{\text{th, OFB}}) \) is the carrier lifetime, \( g \) is the gain coefficient, \( N_o \) is the transparency carrier number, \( \varepsilon \) is the nonlinear gain compression factor, \( R_{sp, \text{OFB}} = (\beta_{sp} N_{\text{sp}} N/\tau_{c, \text{OFB}}) \) represents the contribution of the spontaneous emission of the lasing mode [42], \( \beta_{sp} \) is the spontaneous emission factor, \( N_{\text{sp}} \) is the spontaneous quantum efficiency, \( \alpha \) is the linewidth enhancement factor, \( G_N = \Gamma v_g g/V \), \( \tilde{N} \) is the carrier number time-averaged and \( \bar{F}_N(t), \bar{F}_p(t) \) and \( F_{\phi}(t) \) are the Langevin noise sources due to the carriers, photons and phase, respectively. The authors of [43] and [44] used the gain compression term in form of \((1 - \varepsilon S) \) or \((1 + \varepsilon S)^{-1/2} \). According to [45], the form \((1 + \varepsilon S) \) seems more compatible with the numerical solution. To obtain the noise characteristics, the fluctuations of the variables in Equations (9) are assumed to remain small at all times in comparison with the respective steady-state average values (small-signal approximation). Under this assumption, the rate equations can easily be solved numerically in the frequency domain using Fourier transforms.

The fluctuation of the lasing frequency \( \Delta v(t) \) is described by the variation of the optical phase as [32,34]

\[
\Delta v(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt}.
\]

The random Langevin noise sources in Equations (9) are assumed to be Gaussian random variables due to carriers, photons and phase, respectively. Considering the Markovian assumption, the general relationship between the noise sources can be defined as [42]

\[
\langle F_i(t) \rangle = 0 \quad \text{and} \quad \langle F_i(t), F_j(t') \rangle = 2D_{ij} \delta(t - t'),
\]

where angled brackets denote ensemble averages, \( \delta \) is the Dirac’s delta function and \( D_{ij} \) are diffusion coefficients associated with the corresponding noise source of \( i \) and \( j \), which is defined as [42]

\[
D_{SS} = R_{sp, \text{OFB}} S,
\]

\[
D_{NN} = R_{sp, \text{OFB}} S + \frac{1}{\tau_{c, \text{OFB}}} N,
\]

\[
D_{\phi\phi} = \frac{R_{sp, \text{OFB}}}{4S},
\]

\[
D_{NN} = -\frac{1}{2} R_{sp, \text{OFB}} S,
\]

\[
D_{S\phi} = D_{N\phi} = 0,
\]
where $S$ and $N$ represent the steady-state average values of the photon and carrier populations, respectively. The output power $P_{\text{out}}(t)$ from the front facet of the FGFP laser is given by

$$P_{\text{out}}(t) = \frac{hv}{\tau_{\text{OFB}}} S(t),$$

(17)

where $hv$ is the photon energy of the emitted light. The power can be obtained by solving the equation for photon number $S(t)$. The Fourier transforms of Equations (9), after linearization, yield

$$\tilde{N}(\omega) = \begin{bmatrix} j\omega + h_{11} & h_{12} & h_{13} \\ h_{21} & j\omega + h_{22} & h_{23} \\ h_{31} & h_{32} & j\omega + h_{33} \end{bmatrix} \tilde{h}(\omega) + \begin{bmatrix} \tilde{h}_N(\omega) \\ \tilde{h}_P(\omega) \\ \tilde{\phi}(\omega) \end{bmatrix},$$

(18)

where $h_{ij}$ are the coefficients defined based on the physical model parameters, as expressed in the appendix. The driving terms in Equation (18) are given by the following expressions

$$\tilde{h}_N(\omega) = \tilde{F}_N(\omega)H^{-1}(\omega),$$

(19a)

$$\tilde{h}_P(\omega) = \tilde{F}_P(\omega)H^{-1}(\omega),$$

(19b)

$$\tilde{\phi}(\omega) = \frac{1}{(j\omega)^2} \left( \tilde{F}_\phi(\omega) + \frac{1}{2} \alpha G_N \tilde{N}(\omega) \right),$$

(19c)

where

$$H(\omega) = \Gamma_{\text{VG}} \left( h_{22} - \frac{1}{\tau_{\text{OFB}}} \right) - \omega^2 + \frac{1}{4} \left( h_{22} + h_{11} \right)^2 + j\omega(h_{11} + h_{22}).$$

(20)

Finally, by considering Equations (18)–(20) for the spectral density of the frequency or the phase noise (FN) general equation, $S_\phi(\omega) = |\omega \tilde{\phi}(\omega)|^2$ [42], the spectral density of the frequency or FN of a FGFP laser can be written as

$$S_\phi(\omega) = \frac{2R_{\text{OFB}}}{S} \left[ 1 + \frac{\alpha^2 \beta_{\text{VG}} B N^2 / 2VS \left( \Gamma_{\text{VG}} \left( h_{22} - \frac{1}{\tau_{\text{OFB}}} \right) - \omega^2 \right)^2 + (\omega(h_{11} + h_{22}))^2 \right].$$

(21)

Equation (21) is the main equation that is used in this study to observe the FN characteristics of the FGFP laser.

4. Results and discussion

In this study, the phase noise characteristics of a FGFP laser operating at a 1550 nm wavelength were analyzed.
In addition, at strong reflectivity values, the decay rate of the relaxation oscillation is increased, which damps the maximum value of the phase noise, thereby resulting in a larger flat operation range. This is because the strong optical feedback forces the laser to operate in the coherence field (regime V [25]), which results in pure single-mode oscillation. Furthermore, the relaxation–oscillation frequency (ROF) is increased by increasing the reflectivity value and saturated at strong optical feedback, which is due to the reduction in fluctuations of the gain spectrum in the active region.

Figure 3 shows the effect of injection current on the FN spectrum. As depicted in Figure 3, by increasing the injection current from $2I_{th}$ to the $5I_{th}$, the peak of the FN spectrum is reduced by around 18.3 dB and the ROF is shifted around 2.5 GHz towards higher frequency; thus, a larger flat frequency range is obtained. This is due to the increment of photon density inside the active region, which leads to a reduction of the gain spectrum fluctuation.

The effect of ambient temperature variation on the FN spectrum is shown in Figure 4, where Figure 4(a) represents the result at a temperature of 25°C, Figure 4(b) is for temperatures of 15, 20 and 30°C and Figure 4(c) is for a temperature of 35°C. The effect of temperature was calculated in this study according to the temperature dependence of the laser cavity parameters (Equation (5)) instead of directly using the well-known Parkove equation. From Figure 4, it can be seen that by increasing the temperature from 15 to 25°C, the ROF is shifted by around 2.4 GHz to higher frequency and the peak of phase noise is reduced by around 27 dB. However, further increase in the temperature from 25 to 35°C caused the ROF to shift back toward lower frequency by around 3.15 GHz and the phase peak noise is increased by around 14.6 dB. This is because, according to Equation (5), the maximum reflectivity of the Bragg grating occurs at the temperature $T_0$, which in this study is assumed to be at 25°C. Thus, by increasing the temperature from 15 to 25°C, the shift in the Bragg wavelength is reduced, which causes an increase in the reflectivity. When the reflectivity reaches its maximum value (at 25°C), the FN is reduced to its minimum value, which is due to
the transition of laser operation from the weak to the strong OFB level. On the other hand, the ROF, which is defined as [42]:

$$\text{ROF}(T) = \frac{1}{2\pi} \left[ \frac{1 + G_N V_N(T)\tau_{\text{p,OFB}}(T)}{A_{nr} + BN_{th,\text{OFB}}(T) + C N_{th,\text{OFB}}^2(T)} \right]^{-1} \tau_{\text{p,OFB}}(T) \left( \frac{I}{I_{th,\text{OFB}}} - 1 \right)^{1/2}, \tag{22}$$

depends on the photon lifetime $\tau_{\text{p,OFB}}$ and threshold current $I_{th,\text{OFB}}$ [42], both of which are temperature dependent, as shown in Equations (3) and (6), respectively. Thus, by increasing temperature from 15 to 25°C, $\tau_{\text{p,OFB}}$ is increased and $I_{th,\text{OFB}}$ decreased due to the increment of the reflectivity, which makes ROF shift toward higher frequency. In contrast, when the temperature increases from 25 to 35°C, the reflectivity is reduced due to the shift in the Bragg wavelength; thus, the FN increases due to the transition of laser operation back from the strong to the weak OFB level. On the other hand, when the temperature is increased from 25°C, the reflectivity will be reduced, which causes the $I_{th,\text{OFB}}$ to increase and the $\tau_{\text{p,OFB}}$ to reduce; thus, the ROF shifts back toward lower frequency. Comparing this result against that for a DFB laser at room temperature [32,34] shows that the FGFP laser has around 15 dB lower peak value in its FN spectrum at the same injection current. This result confirms the lower sensitivity of the FGFP laser to temperature in comparison to the DFB laser.

The gain compression factor $\varepsilon$ is another important parameter for semiconductor lasers, which can affect on the phase noise spectra. This is mainly depends on several mechanisms, such as the spatial hole burning, spectral hole burning and other nonlinearities. Figure 5 shows the effect of gain compression factor on the phase noise spectrum of a FGFP laser. By increasing the $\varepsilon$ from $1 \times 10^{-17}$ to $5 \times 10^{-17}$, the decay rate of the relaxation oscillation is increased, which causes a reduction of the peak FN spectrum by around 21.6 dB. In addition, by changing the gain compression factor, the ROF is not changed and maintained at 4.9 GHz.

The volume of the laser cavity has a critical impact on system performance due to its significant effect on the total loss. The increase of active cavity volume increases the threshold current, thereby reducing the output power. This will adversely affect the dynamic behavior properties. Figures 6(a), 6(b) and 6(c) show the effect of cavity volume on FN spectrum for different size of cavity length ($L_d$), thickness ($d$) and width ($w$), respectively. It can be seen that by reducing the cavity volume from $3.2 \times 10^{-10}$ to $1.6 \times 10^{-10}$ cm$^3$ (by reducing any one of the active cavity volume parameters), the ROF is shifted around 3.4 GHz toward higher frequency and the FN spectrum peak value is reduced by around 4.2 dB in Figure 6(a) and 7.36 dB in Figures 6(b) and 6(c). This result confirms the advantage of smaller cavity size for loss reduction. However, further reduction in the cavity length results in very small time delay, which may cause the laser to operate with chaotic dynamics [46,47]. In addition, the smaller cavity thickness and width might slightly reduce the phase noise; however, this condition may increase the design complexity and cost.

The effect of amplitude coupling coefficient ($C_o$) on the FN spectrum is shown in Figure 7. By increasing $C_o$ from 0.3 to 0.9, the ROF is shifted by around 2.4 GHz toward higher frequency and the peak FN spectrum value reduced by around 44.7 dB, which is due to improving the total emitted power.

The effect of the external cavity length ($L_{\text{ext}}$) on the FN spectrum is shown in Figure 8. In this paper $L_{\text{ext}}$ is the distance from the output of the FP laser to the reflection point on the FBG, as can be seen in Figure 1(a). The value of $L_{\text{ext}}$ is in the range of centimeters and independent of the grating length. According to Equation (1), the effective reflectivity $R_{\text{eff}}$ depends on $\cos(\omega_T)$, where $\tau_e$ depends on $L_{\text{ext}}$ as $\tau_e = 2L_{\text{ext}}c/\omega_e$. Thus, any changes in $L_{\text{ext}}$ will affect the effective reflectivity $R_{\text{eff}}$ based on the cosine function, as shown by the inset of Figure 8. Any change in $L_{\text{ext}}$ changes the reflectivity value within a fixed range with the minimum and maximum reflectivity of around 74 and 95%, respectively. The shortest external cavity length

![Figure 5. Effect of nonlinear gain compression factor on FN spectrum. (The color version of this figure is included in the online version of the journal.)](image-url)
that provides the maximum reflectivity value is around 3.1 cm. The maximum reflectivity is repeated with a period of around 3.1 cm. Even though 6.2 cm, 9.3 cm, and so on, can also provide the maximum reflectivity value, the longer external cavity length causes an increase in the delay time ($\tau_d$). Therefore, the shortest external cavity length provides the optimum performance. In terms of FN, a higher reflectivity value provides the minimum FN, which in our case occurs at $L_{ex}$ of around 3.1 cm. As Figure 8 implies, when $L_{ex}$ is equal to 1.55 and 3.1 cm, the peak spectrum of FN is changed from its maximum to minimum value, which is around 2.95 and 0.58 MHz, respectively. The reduction in FN is due to the increment of the reflectivity value, where $R_{eff}$ is increased from 74 to 95% when $L_{ex}$ is increased from 1.55 to 3.1 cm, respectively. When $L_{ex}$ is changed from 1.55 to 3.1 cm, the ROF is shifted from 6.85 to
6.898 GHz, which is only around 40 MHz and not significant. This result shows that the ROF is not significantly affected by \( L_{\text{ext}} \). According to Equation (7), the changes of \( R_{\text{eff}} \) from 74 to 95% does not significantly affect the \( \alpha_{\text{tot,OFB}}(T) \). Therefore, \( \tau_{\text{p,OFB}} \), \( N_{\text{th,OFB}} \) and \( I_{\text{th,OFB}} \), shown in Equations (6), (4) and (3), respectively, are also not significantly affected; thus, based on Equation (22), the ROF will not be significantly changed.

5. Conclusion

The effect of phase noise (FN) on the performance of a FGFP laser diode was investigated numerically. The modified well-known laser rate equations, which include the effects of external optical feedback (OFB) and temperature (\( T \)), have successfully been explored to result in significant findings in this paper. It is shown that the peak value of the FN spectrum is decreased by controlling the OFB level. It is also found that the temperature variation does not markedly affect the FN spectrum of a FGFP laser. Moreover, increasing the nonlinear gain compression factor will increase the decay rate of ROF, thereby resulting in a lower FN peak. Furthermore, the active region volume and the external cavity parameters also contribute towards the characteristics of phase noise. The results from this paper should be very useful for designing, manufacturing and operating the FGFP laser diode as a promising light source with minimum phase noise for optical telecommunication networks.

References

Appendix

The elements $h_{ij}$ in Equation (14) are given by:

$h_{11} = (R_{sp,OFB}/S) + \Gamma_v^2v_g^2$,
$h_{12} = \Gamma_v^2v_g(1 - \Gamma_vS)$,
$h_{13} = h_{23} = h_{31} = h_{32} = h_{33} = 0$,
$h_{21} = \left[V(\Gamma_vS + 2R_BN)\right]^{-1}$,
$h_{22} = (1/\tau_{c,OFB}) + (\Gamma_v^2a_0/V)S$,
$h_{31} = (R_{sp,OFB}/S) + \Gamma_v^2v_g$,
$h_{33} = S - \Gamma_v^2v_g(1 - \Gamma_v)$.