## Broadband chaotic light transmitter

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A broadband- and photonic-integrated convenient chaotic-light transmitter with both optical feedback and mutual optical-coupling techniques are proposed. Both numerical simulation and experimental results show that the bandwidth of the presented transmitter is much higher than that of the traditional transmitter with only the optical feedback or the mutual optical-coupling; and the influence of optical feedback strength and mutual optical coupling strength on the bandwidth is also investigated numerically.

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Applications of chaotic light include secret optical communication, high-speed random number generation, photonic reservoir computing, etc.<sup>[1-3]</sup>. In all these areas, the quantity of information that the chaotic carrier can hide or the number of transient states essential for information processing is directly determined by the bandwidth of the chaotic light. As a result, broadband chaotic light transmitters have attracted much interest. Traditional transmitters are mainly based on optical feedback<sup>[4]</sup>, electro-optical feedback<sup>[5]</sup>, optical injection<sup>[6]</sup> and mutual optical coupling<sup>[7]</sup>, and could be implemented through bulk devices<sup>[8]</sup> or photonic integrated chips<sup>[9]</sup>.

However, only one of the techniques mentioned above is utilized in most of the traditional chaotic light transmitters. This makes a very limited range of key parameters available that make the transmitter a chaos regime, i.e., it is difficult to control the transmitters to generate chaotic light signals; hence, the bandwidth of the chaos light is not greater than 5 GHz. In a study conducted by Li et al.<sup>[10]</sup>, a broadband chaotic light transmitter, which is a combination of optical feedback with optical injection, has been developed by numerical simulation; however, the integrating process of the ring laser needs to be more accurate than traditional Fabry-Perot (F-P) or distributed feedback (DFB) lasers, and the optical isolator is not suitable for integration implementation. Therefore, a chaotic light transmitter, which easily generates broadband chaotic light and which is implemented conveniently by the photonic integrated chip, is designed.

A broadband- and photonic-integrated convenient chaotic-light transmitter with both optical feedback and mutual optical coupling techniques is proposed in this paper. Both numerical simulation and experimental results show that the bandwidth of the presented transmitter is much larger than that of the traditional chaotic-light transmitter. Additionally, as the optical isolator is not employed in the transmitter, the structure is available for design and fabrication through photonic-integrated techniques. Figure 1 shows the scheme of the transmitter. The master laser is subjected to optical feedback to operate at the chaos state. Meanwhile, the master (DFB-M) and the slave (DFB-S) lasers couple with each other, and the chaotic laser is emitted from the slave laser.

The dynamic behavior of two lasers of the structure can be described by rate equations<sup>[11]</sup>

$$\frac{dE_{1}(t)}{dt} = \frac{1}{2} \left(1 + i\alpha\right) \left\{ \frac{G\left[N_{1}(t) - N_{0}\right]}{1 + \varepsilon \left|E_{1}(t)\right|^{2}} - \frac{1}{\tau_{\mathrm{P}}} \right\} E_{1}(t) + \kappa_{\mathrm{r}} E_{1}(t - \tau) \exp\left(-i\omega\tau\right) + \kappa_{\mathrm{c}} E_{2}(t), \quad (1)$$

$$\frac{dN_{1}(t)}{dt} = \frac{I_{1}}{qV} - \frac{1}{\tau_{n}}N_{1}(t) - \frac{G\left[N_{1}(t) - N_{0}\right]}{1 + \varepsilon \left|E_{1}(t)\right|^{2}} \left|E_{1}(t)\right|^{2}, \quad (2)$$

$$\frac{dE_{2}(t)}{dt} = \frac{1}{2} (1 + i\alpha) \left[ \frac{G\left[N_{2}(t) - N_{0}\right]}{1 + \varepsilon \left|E_{2}(t)\right|^{2}} - \frac{1}{\tau_{\mathrm{P}}} \right] E_{2}(t) + \kappa_{\mathrm{c}} E_{1}(t), \qquad (3)$$

$$\frac{dN_{2}(t)}{dt} = \frac{I_{2}}{qV} - \frac{1}{\tau_{n}}N_{2}(t) - \frac{G\left[N_{2}(t) - N_{0}\right]}{1 + \varepsilon \left|E_{2}(t)\right|^{2}} \left|E_{2}(t)\right|^{2}, \quad (4)$$

where, E and N represent the slowly varying complex electronic field amplitude and the carrier density in the laser cavity, respectively;  $\omega$  is the angular frequency



Fig. 1. Scheme of the transmitter.

Table 1.	Parameters	and	their	values
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Symbol	Parameter	Value
$ au_{ m in}$	Round-trip time in the laser cavity	$9 \times 10^{\text{-12}}  \mathrm{s}$
$r_0$	Reflectivity of the laser facet	0.3
$K_{\rm r}$	Reflectivity of the external mirror	$10~\mathrm{ns}^{-1}$
K	Coupling strength	$20~\mathrm{ns}^{-1}$
α	Linewidth enhancement factor	4.5
G	Gain coefficient	$2 \times 10^{-12}  m^3/s$
$N_{_0}$	Carrier density at transparency	$10^{24} \text{ m}^{-3}$
ε	Gain saturation coefficient	$3\times 10^{23}m^3$
$ au_{ m P}$	Photon lifetime	$2\times 10^{\text{-12}}\mathrm{s}$
q	Charge quantity	$1.6\times10^{\scriptscriptstyle -19}\rm C$
V	Volume of the active region	$1.5 \times 10^{\text{-16}}\mathrm{m^{3}}$
$ au_{ m n}$	Carrier lifetime	$2\times 10^{-9}\mathrm{s}$

of the free-running laser;  $\kappa_{\rm r}$  and  $\kappa_{\rm c}$  are the feedback strength and the mutual coupling strength, respectively;  $I_1$  and  $I_2$  are injection currents of master and slave lasers, respectively, and  $i = \sqrt{-1}$  is the unit of imaginary number.

From Eq. (2), it is known that these two parameters play an important role in the output of the laser, and thus, the influence of them on the chaotic light bandwidth will be detailed in the subsequent section. Definitions and values of other parameters used in the simulation are listed in Table 1.

The DFB-M with only optical feedback forms the traditional chaotic light transmitter. According to the parameters in Table 1, the output of DFB-M is obtained by the simulation, is shown in Fig. 2.

From Fig. 2 it is observed that the bandwidth of the transmitter realized only by optical feedback is approximately 5.71 GHz. Here, the bandwidth is defined as the frequency range between DC and the frequency that contains 80% of the spectral power. Then, the DFB-S and the mutual optical coupling between DFB-M



Fig. 2. Output of the traditional transmitter with only optical feedback (a) Waveform in time domain and (b) radio-frequency (RF) spectrum.

and DFB-S are simultaneously introduced to form the proposed transmitter. To analyze the property of the transmitter, the mutual coupling strength is fixed at 20 ns<sup>-1</sup>, and the output of the transmitter under different feedback strengths is shown in Fig. 3. It can be observed that the bandwidth of the transmitter is stabilized near 7 GHz. This indicates that the feedback strength of the master laser has little influence on the bandwidth of the transmitter.

Then, the feedback strength is fixed at 10 ns<sup>-1</sup>, and the bandwidth of the transmitter under different mutual coupling strengths is obtained as shown in Figs. 4 and 5.

It is observed from Fig. 4 that the bandwidth of the transmitter increases with the increasing mutual coupling strength, which means that the mutual coupling influences significantly on the bandwidth. When the mutual coupling strength increases up to 160 ns<sup>-1</sup>, the bandwidth of the transmitter can exceed 20 GHz, as shown in Fig. 5, which is much larger than that of the traditional transmitter. Therefore, for this type of trans-



Fig. 3. (a) Waveform and (b) RF spectrum of the outputs for the proposed transmitter with the fixed mutual coupling strength of 20 ns<sup>-1</sup> under different feedback strengths. (a1) and (b1) The feedback strength is 12 ns<sup>-1</sup>; (a2) and (b2): the feedback strength is 20 ns<sup>-1</sup>; (a3) and (b3) The feedback strength is 28 ns<sup>-1</sup>.



Fig. 4. (a) Waveform and (b) RF spectrum of the proposed transmitter with the fixed feedback strength of 10 ns<sup>-1</sup> under different mutual coupling strength—(a1) and (b1) 10 ns<sup>-1</sup>; (a2) and (b2) 20 ns<sup>-1</sup>; and (a3) and (b3) 40 ns<sup>-1</sup>.



Fig. 5. Bandwidth of the chaotic-light transmitter versus the mutual coupling strength.

mitter, the mutual coupling between the master and slave lasers plays an important role on the bandwidth.

To identify which factor influences more on the bandwidth, the effect of both mutual coupling strength (solid line) and feedback strength (dash line) on the bandwidth is shown together in Fig. 6. The bandwidth increases gently with the feedback strength when the mutual coupling strength is fixed. However, when the feedback strength is fixed, the bandwidth increases sharply with the mutual coupling strength.

The experimental setup of the proposed broadband- and photonic-integrated convenient chaotic-light transmitter is shown in Fig. 7. The feedback loop is formed by an optical circulator and two 50/50 optical couplers. Meanwhile, the mutual coupling route is



Fig. 6. Effect of mutual coupling strength (solid line) and feedback strength (dash line) on the bandwidth.



Fig. 7. Experimental setup of the proposed broadband- and photonic-integrated convenient chaotic-light transmitter.

formed by two couplers. The feedback strength and the mutual coupling strength are controlled by three variable optical attenuators. An optical spectrum analyzer (Anritsu MS9740A) and a 20-GHz optical serial data analyzer (Lecroy SDA 820Zi-A) are employed to measure the optical spectrum, waveform and the RF spectra of the emission of light from the two lasers. In this experiment, the injection current of both the lasers was 20 mA. The wavelength of the DFB-M was stabilized at 1554.76 nm, and that of DFB-S is at 1554.75 nm. The feedback ratio was set at 2%, and the mutual coupling strength was set at 6%.

As shown in Figs. 8(b) and (d), when the mutual coupling between the master and slave lasers is introduced, the oscillation of the waveform is more intense, and the power of the high-frequency component of the RF spectrum increases significantly. In order to clearly exhibit the enhancement of the bandwidth, the data of the RF spectrums are fitted (Fig. 9). It is shown that the bandwidth increases from 6.9 GHz for only optical feedback to 17.8 GHz for combining optical feedback with mutual coupling.



Fig. 8. Output of the transmitters. (a) and (c) are waveform and RF spectrum of the transmitter with only optical feedback, respectively, (b) and (d) are those of the proposed transmitter.

The final optical spectrum is shown in Fig. 10. The width of the optical spectrum is broad, which verifies that the proposed transmitter can generate broadband chaotic light.

A broadband chaotic laser transmitter realized by combining optical feedback with mutual optical coupling is proposed. The bandwidth of the transmitter is evaluated as a function of the optical feedback strength and the mutual coupling strength; and the experimental results show that the bandwidth of the proposed transmitter is nearly three times greater than that of the traditional transmitter. For this type of transmitter, the mutual coupling strength has a more significant effect on the bandwidth. As there is no optical isolator in this proposed structure, it is suitable for photonic integration implementation.



Fig. 9. Fitted RF spectrum.



Fig. 10. Optical spectrum of the transmitters. (A) Optical spectrum of the master laser. (B) Optical spectrum of the transmitter with only optical feedback. (C and D) Optical spectrum of the proposed transmitter.

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