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Mode Selective Active Multimode Interferometer Laser Diode —Mode Selection Principle, and High Speed Modulation—

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SUMMARY We have proposed and demonstrated a mode selective active-MMI (multi-order interferometer) laser diode as a mode selective light source so far. This laser diode features: 1) lasing at a selected space mode, and 2) high modulation bandwidth. Based on these, it is expected to enable high speed interconnection into future personal and mobile devices. In this paper, we explain the mode selection, and the high speed modulation principles. Then, we present our recent results concerning high speed frequency response of the fundamental and first order space modes.

key words: active-MMI, mode selective light source, high modulation bandwidth, direct modulation

1. Introduction

The performance of supercomputer is advancing sharply due to recent progress of artificial intelligence, big data, and other technologies. For further performance, higher interconnection speed is important in addition to processor ability as it may limit the total system performance, and thus it is forecasted that interconnection speeds will exceed Tbps in the near future [1]. The history of technology predicts that a similar performance may be also realized in mobile and personal devices. In 10–20 years, over Tbps interconnection, based on optical communication, is expected for mobile and personal devices. One possible way is to utilize E/O (electric/optical) signal exchange at the interface of CPU (central processor unit) and then to transmit high speed signal along flexible and low cost waveguide like polymer [2]. In this case, it is desired to integrate single light source (laser diode: LD) due to limited space and the cost issues with the devices, and therefore it is desired to integrate very high speed direct modulation LD.

While the speeds of direct modulation LD are limited up to around 40–50 Gbps presently [3]–[5], it is necessary to raise up this performance 20 fold to achieve “toward over Tbps” transmission speeds. In addition to it, the fundamental potential of light as transmission frequency is much higher. For instance, wavelength of 1550 nm is approximately 200 THz in frequency which corresponds essentially to the physical maximum modulation speed limit. Even from an academic point of view, it is important to clarify the physical constraints on the speed limit of the direct modulation.

For the purpose mentioned above, we have proposed and demonstrated a mode selective light source of which $1 \times N$ active-MMI (multi-mode interferometer) LD configurations has been exploited to [6], [7]. This LD features; 1) Lasing at a selected space mode, and 2) High modulation bandwidth

Based on the combination of mode multiplexing and high speed modulation, $N$-fold ($N$: possible mode number) enhancement of a direct modulation signal could be realized by this light source. For instance, if an $N$-mode selective light source can be realized with a 100Gbps direct modulation on each space mode, this single light source would have the potential of delivering $N$ times of 100Gbps, and in case of $N$ over 10, the potential exceeds Tbps. Note that this high modulation bandwidth is based on multiple photon-photon resonance, which is brought by using plural oscillation paths inside the cavity [8]. The plural oscillations are realized by using multiple paths mainly, therefore, the plural paths themselves are less related to the spatial lateral output mode. Consequently, each individual spatial lateral output mode is operated with high speed modulation [9].

In this paper, we explain the mode selection, and the high speed modulation principles. Then, our recent results of 0th and 1st order mode emission with high speed frequency response (over 40 GHz) are presented.

2. Device Principle

2.1 Mode Selection

We exploited $1 \times N$ ($N$: natural number) active-MMI (multi-mode interferometer) configuration to mode selective light source. To explain the mode selection principle, here we consider a (passive) waveguide structure that splits power into two waveguides. When fundamental mode (TE$_{00}$) light is injected from single narrow waveguide side which is placed at the left hand side (LHS), it is separated mostly into two narrow waveguides at the right hand side (RHS) via a properly designed multimode interference (passive) waveguide as shown in Fig. 1 (a) and (b). Please note that the narrow waveguide at the LHS is connected, not at the center, upper side of MMI, and the separated light goes into two waveguides as one at the center and one at the lower positions as shown in Fig. 1 (a). A similar situation also occurs for the 1st order mode (TE$_{01}$) as shown in Fig. 1 (c) and (d). When the 1st order mode is injected from the single narrow waveguide side as shown in Fig. 1 (c), the injected light...
is separated mostly into two narrow waveguides at the RHS via the same MMI waveguide. Please note that the separated light goes into two waveguides as one in the center and one in the upper positions, unlike the fundamental mode case, while the narrow waveguide at the LHS keeps the same position as in the fundamental mode separation case explained above. This means that:

1) The narrow waveguide at the LHS and MMI are shared between fundamental and 1\textsuperscript{st} order modes;
2) The narrow waveguide at the bottom of the RHS is used only by the fundamental mode;
3) The narrow waveguide at the top of the RHS is used only by the 1\textsuperscript{st} order mode.

The position difference of the separated light at the RHS shown above is caused by the different propagation constants of the fundamental and 1\textsuperscript{st} order modes.

Then, we consider turning all waveguides into “active” waveguides, and also consider separating electrodes into three regions corresponding to the waveguide regions explained above as;

Electrode 1) Pumping section electrode
MMI, and narrow center waveguide at the RHS
Electrode 2) Fundamental mode selection electrode
Narrow waveguide at the RHS bottom
Electrode 3) 1\textsuperscript{st} order mode selection electrode
Narrow waveguide at the RHS top

By controlling current injection into electrodes 2 and 3, the oscillating mode can be selected, this is the principle of mode selection. In addition to the electrodes explained above, we also separated the narrow waveguide at the LHS into a modulation section.

2.2 High Speed Modulation

It is well known that the frequency response of LD is constrained by its relaxation oscillation frequency. This oscillation phenomenon is called CPR (carrier photon resonance). The CPR frequency $f_r$ is enhanced when the photon density in the LD cavity is enhanced, and then high frequency response is achievable. For this reason, many efforts to enhance photon density in the LD cavity have been made so far. Generally speaking, one of the most effective ways to enhance $f_r$ is to shorten the cavity length; to date, 40–50 Gbps direct modulation LDs have been reported and implemented [5], [10], [11].

One of the further high speed modulation techniques may be photon photon resonance (PPR) [12]. It has been reported that the PPR frequency appears to be higher than CPR frequency $f_r$. If the PPR frequency is available, it may be expected to have a higher frequency response, leading to higher direct modulation compared to $f_r$.

There is, however, one issue when PPR frequency is adopted, as illustrated in Fig. 2. The frequency response between CPR and PPR may be degraded to below $-3$ dB as shown in Fig. 2(a). In this case, frequencies higher than CPR are not available for the actual direct modulation. For this reason, the PPR frequency must be set closer to the CPR frequency to avoid the situation explained above, and to avoid degradation below $-3$ dB in frequency response in between CPR and PPR as shown in Fig. 2(b). It means, therefore, CPR still limits the maximum frequency response as PPR can not be set apart from CPR.

To side-step this issue with CPR limiting the maximum frequency response, utilizing plural PPR scheme has been proposed and demonstrated [13]–[15]. Figure 2(c) shows the concept of this scheme. Frequency degradation occurs when two frequency response peaks are separated by a relatively wide gap in frequency. As shown in Fig. 2(c), if each
of the PPR frequencies is placed closer than in Fig. 2 (a), it may be possible to avoid frequency degradation below −3 dB up to the maximum PPR frequency.

In general, PPR has been reported to be strongly related to the multiple resonances in LD and the PPR frequency therefore, plural sub-peaks in wavelength must be designed in a single LD device in order to realize plural PPR. Since the 1 × N MMI configuration offers the possibility of multiple interference, causing sub-peaks in wavelength, plural F_{PPR} is enabled.

We utilize the phase matching effect in a 1 × N MMI waveguide to design sub-peaks in wavelength. Again we consider the passive MMI waveguide here as an example to consider this phase matching condition. In case of designing 1 × 3 MMI on the LHS of Fig. 3, the injected light from 1 port is divided into three beams of equal power, while the phase at the 3 port side are different from each other (see in the middle of Fig. 3). If all light is injected again into the same MMI waveguide as the 3 × 1 configuration vice-versa as shown on the RHS of Fig. 3, the necessary phase condition is no more kept at the 3-port side that results in a huge loss. Because LD is a device in which light propagate back and forward as an oscillation, if the LD waveguide configuration is as shown in Fig. 3, there will be a huge loss in the cavity that may result in no lasing at the end.

To avoid this phase mismatching condition, we should consider to realize phase matching. Figure 4 shows an example of a phase matching condition. As shown in the figure, bending waveguide is connected at the 3-port side, and the phase in the middle is tuned. In this case, even if all the light is injected again into the same MMI waveguide as the 3 × 1 configuration vice-versa as shown on the RHS of Fig. 4, the necessary phase condition is satisfied at the 3-port side that result in less excess loss. If an LD waveguide configuration is with this Fig. 4, this LD will lase at the end.

Please note that bending waveguides are introduced to satisfy the phase matching condition in between the 1 × 3 + 3 × 1 MMI configuration (corresponding to lasing oscillation). As the effective light path length changes as wavelength shifts, the phase matching condition shown in Fig. 4 only occurs at a wavelength that satisfy the phase matching condition, while this phase matching is no more

\[ F_{PPR} = \frac{\Delta \lambda \cdot c}{\lambda^2} \]

where

- \( \lambda \): wavelength
- \( \Delta \lambda \): wavelength difference between main peak and sub-peaks
- \( c \): light speed
The principle of this ripple is explained as follows. The ripple spacing is controlled by using the design of the bending waveguide (here we call it as \( \Delta L \)) which is slightly different from \( \Delta L \) in step 2 above. By adding additional arms by enhancing the number “N” using different connecting bending waveguide radii. This is the way how to realize multiple desired sub-peaks in wavelength that results in multiple PPRs in frequency.

One typical way is to utilize the bending radius to change this \( \Delta L \) (steeper bending radius leads to larger \( \Delta L \) which results in a narrower ripple spacing \( \Delta \lambda_{\text{ripple}} \)). Please note that a chip length of a LD is given by the cleaving position, whereas \( \Delta L \) itself is decided by the length difference between two waveguides; therefore, \( \Delta L \) (and consequently \( \Delta \lambda_{\text{ripple}} \)) is precisely designed and realized according to the waveguide design itself and, thus, is independent of cleaving position error. As shown in Fig. 5, it is clear that a chip length of a LD is given by the cleaving position, whereas \( \Delta L \) itself is decided by the length difference between two waveguides; therefore, \( \Delta L \) (and consequently \( \Delta \lambda_{\text{ripple}} \)) is precisely designed and realized according to the waveguide design itself and, thus, is independent of cleaving position error. As shown in Fig. 5, it is clear that 1 \( \times \) N MMI configuration may have a few sub-peaks caused by this phase matching effect.

Here we explain the design steps of multiple PPR peaks based on Eqs. (1) and (2).

Step 1: Select the PPR peak in frequency

Based on Eq. (1), \( F_{\text{PRR}} \) is designed by using \( \Delta \lambda \). For example, when selecting 25 GHz as \( F_{\text{PRR}} \), the required \( \Delta \lambda \) is calculated to be 0.4 nm (in case center wavelength = 1550 nm).

Step 2: Design \( \Delta L \) to realize required \( \Delta \lambda \)

Once \( \Delta \lambda \) is decided, the next step is to decide \( \Delta L \). From Eq. (2), \( \Delta L \) is derived as Eq. (4):

\[
\Delta \lambda = \frac{n_{\text{eq}}}{m} \left( \frac{2 \phi + 2 \pi m}{2 \phi + 2 \pi (m + 1)} \right) - \lambda_{\text{center}}
\]  

(4)

Here, \( \lambda_{\text{center}} \) is the center wavelength, which is given by the transmittance peak wavelength of the MMI waveguide. From Eq. (4), \( \Delta L \) is derived as Eq. (5):

\[
\Delta L = \frac{n_{\text{eq}}}{2} \cdot (\lambda_{\text{center}} + \Delta \lambda) \cdot (2 \phi + 2 \pi m)
\]  

(5)

Please note that there may be several choices for \( \Delta L \) depending on integer \( m \). The value \( m \) may affect also the strength of interference between the main and the sub peaks in a wavelength spectrum. Presently we are still on the way of research regarding which \( m \) may be best for obtaining a flat frequency response, because the reported PPR theory has not yet clarified the dependency of the interference intensity.

Step 3: Design another peak by introducing different bending waveguide

Toward obtaining multiple \( F_{\text{PRR}} \), we need to have another arms (another bending waveguide) to have another \( \Delta L \) (here we call it as \( \Delta L' \)) which is slightly different from \( \Delta L \) in step 2 above. By adding additional arms by enhancing the number “N” using different connecting bending waveguide radii. This is the way how to realize multiple desired sub-peaks in wavelength that results in multiple PPRs in frequency.

Note that we are still on the way to finding a proper \( F_{\text{PRR}} \) adjacent distance in frequency suitable for direct signal modulation. We expect that further research about changing this design parameter (bending waveguide radii)

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\begin{equation}
\Delta \lambda = \frac{n_{\text{eq}}}{m} \left( \frac{2 \phi + 2 \pi m}{2 \phi + 2 \pi (m + 1)} \right) - \lambda_{\text{center}}
\end{equation}

(4)
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\begin{equation}
\Delta L = \frac{n_{\text{eq}}}{2} \cdot (\lambda_{\text{center}} + \Delta \lambda) \cdot (2 \phi + 2 \pi m)
\end{equation}

(5)
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will tell us the proper $F_{ppr}$ adjacent distance in frequency in the near future.

3. Mode Selective Light Source with High Frequency Response

We exploited the abovementioned principle of mode selection in addition to plural PPRs in the mode selective light source. Figure 6 illustrates the schematic of the implemented LD. As shown in the figure, three narrow waveguides are connected at the LHS of the MMI waveguide while one narrow waveguide is connected at the RHS. The LHS of the device is the rear side, while the RHS corresponds to front. To satisfy the phase matching condition at the 3-port side of the MMI waveguide, the upper and lower narrow waveguides are consisted of bending waveguides.

All narrow waveguides connected to the MMI waveguide are with a width of 4.5 μm which allows 1st order mode excitation. The width and length of the MMI are 15 μm and 350 μm, respectively, and the length of the straight waveguide at the front side is 50 μm. The total device length is 490 μm. All regions are active waveguides, and the electrodes for mode selection in addition to the front straight waveguide, which is for modulation, are electrically separated and different contact pads were formed on the implemented device. Regular 7 layers InGaAsP/InGaAsP multiple quantum well (MQW) active layer, which was grown by using MOVPE (metal-organic vapor phase epitaxy), was used for the active layer, and the high mesa waveguide was formed by using dry-etching method. Both facets of the implemented device were as cleaved, and evaluated under a 25◦C temperature controller.

Figure 7 shows the emission spectrum of the fabricated device. The top of this figure shows the emission spectra of the 0th order mode selected while the bottom shows that of 1st order mode selected. The emission spectrum for the both modes are no more single wavelength emission: however, only several peaks are seen based on Bernier effect of 1×N active-MMI. In addition, the emission peaks in the both modes differ from each other. This might be due to the propagation constant difference in the active-MMI waveguide, which implies that different mode oscillation happens with each mode. Note that in Fig. 7, the emission wavelength is no longer a single wavelength, unlike in the previous results [11]. Further research may improve the emission spectrum in the future.

Figure 8 shows the evaluated near field patterns of the fabricated device. Mode selection was performed under the conditions summarized in Table 1. As shown in Fig. 8, selected 0th order mode emission (Fig. 8 (a)), selected 1st order mode emission, and both modes simultaneous emission (Fig. 8 (c)) were observed, respectively. Note that each mode was realized in stable condition in a current range of a few 10 mA [16].

We also evaluated the small signal frequency response of both modes using a vector network analyzer (Anritsu 37369D-R). Figure 9 shows the results. The upper panel shows the result for the 0th order mode, while the lower one shows that for the 1st order mode. As shown in the figures, at least more than 40 GHz frequency responses were successfully observed experimentally [16]. At present, we have not yet evaluated responses higher than 40 GHz due to our equipment limit: therefore, we hope to evaluate the response at more than 40 GHz, in addition to large signal modulation. Note that this frequency response was relatively flat while there was no special effort made toward capacitance and resistance optimization. So-called roll-off is avoided due to the first PPR peak [12], [17]. In addition, high photon density at the modulation section which was brought by MMI.
section [18] also contributes to the less roll-off response at higher frequency than the CPR. Further analysis related to the roll-off should be performed in detail in the future. In this study, we have confirmed that both modes can be modulated with very high frequency, and it seems that there is no significant difference between different mode emissions. We used a common modulation section for both modes in this work: however, we plan to change the modulation section to be integrated into future high speed interconnections in compact IT devices and others. For the actual deployment, research on noise in this LD must be implemented.

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### References


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