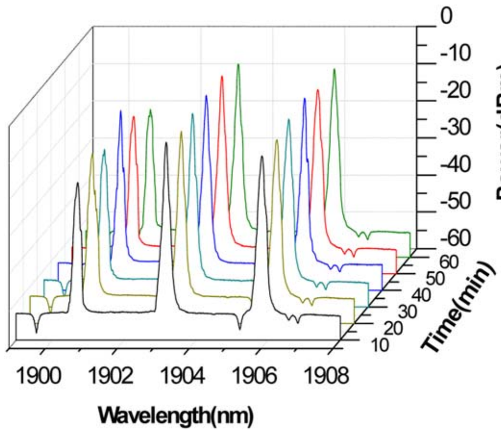


**Figure 5** Output laser spectrum of the triple-wavelength fiber laser at 1.9 µm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

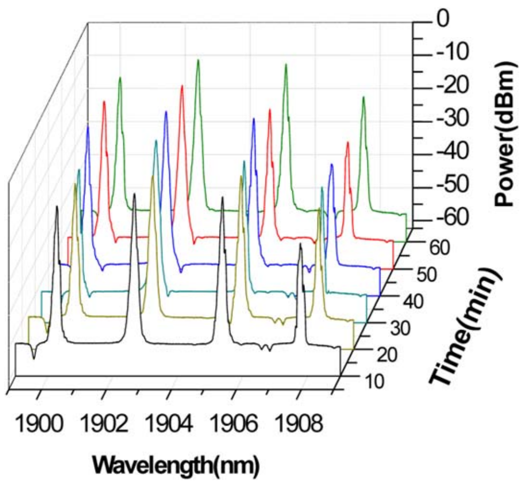


**Figure 6** Output laser spectrum of the four-wavelength fiber laser at 1.9 µm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

## 4. CONCLUSION

A multiwavelength tunable narrow TDF laser around 1.9 µm based on Sagnac fiber loop filter has been proposed and demonstrated. The output wavelength number can be tuned from 1 to 4 by adjusting the PC state. The single-wavelength tunable region is about 20 nm (1895–1915nm). This multiwavelength TDF laser has the advantages of simple structure, low threshold, high SMSR, and narrow linewidth.


## ACKNOWLEDGMENT

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# A HIGH-DENSE WDM LIGHT SOURCE BASED ON MIXING-MODULATED FABRY–PEROT LASER DIODES


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**ABSTRACT:** *A scheme of high-dense wavelength-division-multiplexing light source based on external mixing-modulated Fabry–Perot laser diode (FP-LD) is investigated in this article. A 10-GHz spaced 22-channel optical carrier supply module is achieved by cascading a multiple-longitudinal mode FP-LD with two types of external modulators. Then a 110-channel extendable light source scheme is proposed.*

*This scheme has potential application prospect in future optical access network.*  Microwave Opt Technol Lett 57:403–406, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28857

**Key words:** *wavelength-division-multiplexing; Fabry–Perot laser diode; external modulation; access network*

## 1. INTRODUCTION

Wavelength-division-multiplexing passive optical network (WDM-PON) is considered as an important technology for the future optical access network, because it can provide higher bandwidth per channel compared to nowadays widely applied EPON/GPON technology. In addition, it is easier to arrange safe and unshared services. Super-dense WDM is a feasible migration to extend information capacity using narrower channel spacing. The conventional method which uses many separate laser diodes needs bulky volume and consumes a lot of power [1–9]. There are also some other methods based on wavelength-swept light source, which can be combined with time-domain interleaving technique to increase transmission rate [10].

A Fabry–Perot laser diode (FP-LD) whose intrinsic optical spectrum is multiple-longitudinal can be used for super-dense WDM light source. Narrower intrinsic mode spacing can be obtained by extending the resonant cavity length. However, due to physical limit to the cavity length, the laser cannot directly produce 10-GHz spaced channels. External mixing-modulation is a good method to increase the number of channels by generating sidebands. Therefore, a feasible scheme using FP-LDs with optimized cavity length combining with external mixing-modulation technology can help to produce continuous high-dense WDM channels.

In this scheme, hundreds of WDM channels can be provided using a few FP-LDs, which are more cost-efficient than using DFB-LDs or DBR-LDs. Besides, the channel spacing from one FP-LD is very stable relatively which is constrained by Fabry–Perot cavity. It only needs to control the central wavelength of each FP-LD to match the WDM channels.

In this study, we investigated the scheme mentioned above and proposed a scheme of extendable super-dense WDM light source.

## 2. PRINCIPLE

When small signal intensity and phase modulation is applied to the output lightwave from a single longitudinal mode laser or one mode from a multiple-longitudinal mode laser, the changed optical field can be described as below [11,12]:

$$E(t)=E_0\sqrt{1+M_\mathrm{I}\cos(\omega_\mathrm{m}t)}\,\mathrm{e}^{i[\omega_0 t+M_\mathrm{P}\sin(\omega_\mathrm{m}t+\theta)]} \quad (1)$$

Here, $E_0$ and $\omega_0$ are intrinsic optical field and angular frequency of the laser; $M_\mathrm{I}$ and $M_\mathrm{P}$ are intensity and phase modulation coefficient, respectively; $\omega_\mathrm{m}$ is the microwave angular

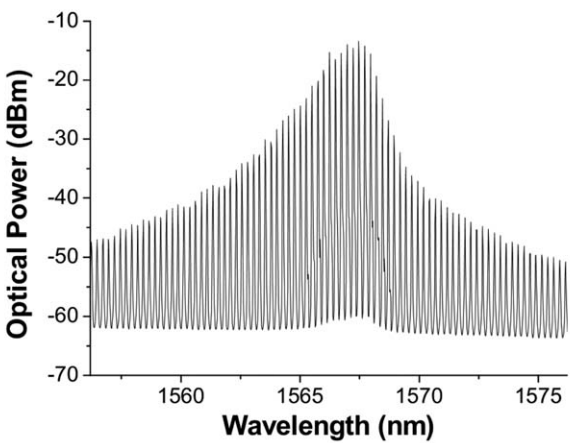


**Figure 1** The original optical spectrum of the FP-LD

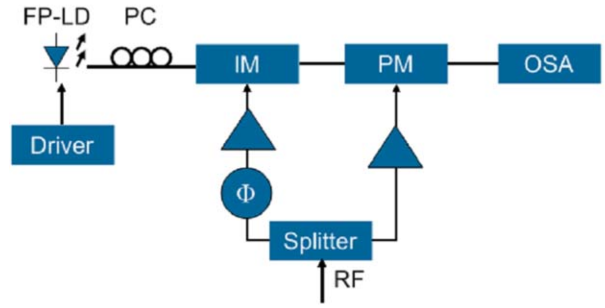


**Figure 2** Experimental setup using a mixing-modulated FP-LD. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

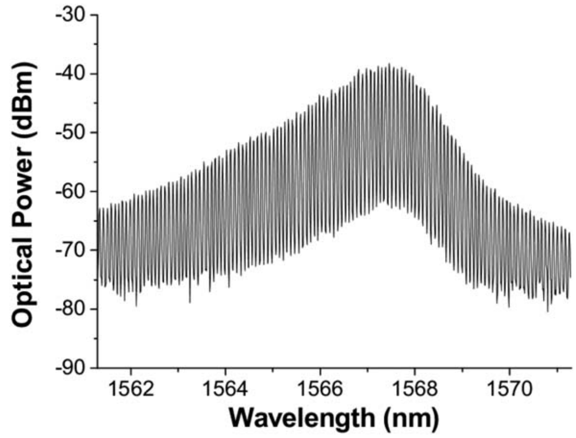


**Figure 3** Optical spectrum with 10 GHz channel spacing. The wavelength range is from 1561.30 to 1571.30 nm

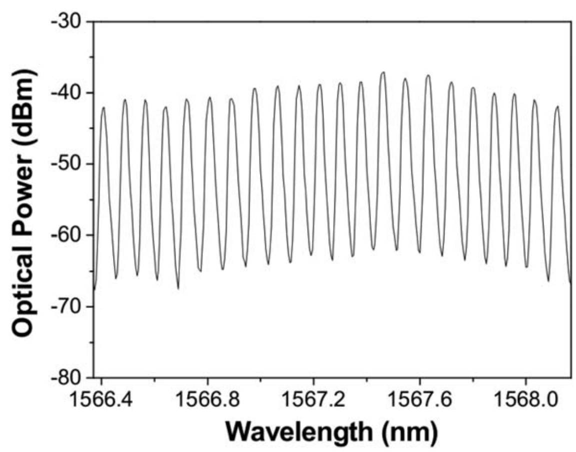


**Figure 4** Optical spectrum of 10-GHz spaced 22 channels. The wavelength range is from 1566.41 to 1568.12 nm. The optical power range is between −42.0 and −37.1 dBm

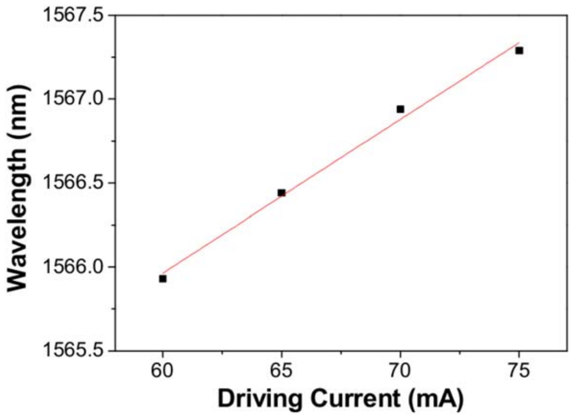


**Figure 5** The wavelength of the WDM light source versus driving current when the chip temperature of the FP-LD chip is 25°C. The solid curve is linear fitting result. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

frequency applied to modulators; and $\theta$ is the phase difference of intensity and phase modulation. When $M_I << 1$ in situation of small signal modulation, the optical field can be expanded by Bessel function, and the optical intensity of n-order sideband can be expressed as below:

$$I_n = I_{orig} J_n^2(M_P)\left(1 + n\frac{M_I}{M_P}\cos\theta\right) \quad (2)$$

where $I_{orig}$ is original optical intensity of the laser without any modulation; $J_n(x)$ is $n$-order Bessel function. When the intensity modulator (IM) and the phase modulator (PM) are cascaded and applied with microwave modulation signals from one source, $\theta$ could be adjusted to zero. Besides, when $M_P << 1$, $J_0(M_P) >> J_1(M_P) >> J_2(M_P)$. Therefore, $I_0 \approx I_1 >> I_2$ could be achieved by changing the value of $M_I / M_P$, which means if microwave with proper frequency is introduced and the modulation depth of intensity and phase modulation is adjusted carefully, zeroth-order and first-order modes with even optical intensity from a multiple-longitudinal mode laser with mixing-modulation could be obtained and be used as channels of high-dense WDM system.

## 3. EXPERIMENT AND RESULT

The intrinsic mode spacing of a FP-LD is inversely proportional to the length of resonant cavity. However, too long resonant cavity will result in high threshold current, high power consumption, high heat, and low reliability. Besides, the intrinsic mode spacing should also be integral multiple of the designed WDM channel spacing by precise control of the resonant cavity length. We fabricate a multiple-longitudinal mode FP-LD with about 1.2 mm resonant cavity for the experiment. It is butterfly-shaped package with TEC. A current driver and chip temperature controller were also used. The threshold current of the FP-LD was about 55 mA. The original spectrum is shown in Figure 1. The intrinsic longitudinal mode spacing was 30.0 GHz. The central wavelength is 1567.46 nm with optical power of −13.4 dBm. The chip temperature was 25°C and the driving current was 80 mA.

The experimental configuration is shown in Figure 2. The multiple-longitudinal-mode FP-LD was used to provide seed carriers. The $LiNbO_3$ IM and $LiNbO_3$ PM were cascaded to generate even sidebands. The RF was divided by a splitter and applied to the IM and the PM, respectively. The two routes of RF were both preamplified. The phase shifter is used to match the phase of sidebands generated by IM and PM. The polarization controller was used to maximize the modulation efficiency. The output spectrum was observed by an optical spectrum analyzer with 0.02 nm resolution. The frequency of RF should be equal to the designed WDM channel spacing. In this experiment, the RF frequency was 10.0 GHz.

In the experiment, the RF power injected into the PM and IM and the phase shifter should be tuned carefully to weaken the zeroth-order modes, which are the intrinsic modes from the FP-LD and gain the first-order sidebands produced by external modulators. Thus, smooth high-dense WDM channels were obtained, as shown in Figure 3. The wavelength range is from 1561.30 to 1571.30 nm. It shows that there is an even wave-range near the central wavelength and the optical power declines rapidly out of this range. For the purpose of application, 10-GHz spaced 22-channels near the central wavelength are selected out, as shown in Figure 4. The wavelength range is from 1566.41 to 1568.12 nm. The maximum optical power is −37.1 dBm at 1567.46 nm (central wavelength), whereas the minimum optical power is −42.0 dBm at 1566.41 nm ($\Delta P_{max} = 4.9$ dB). The optical signal noise ratio of all 22 channels is more than 23 dB.

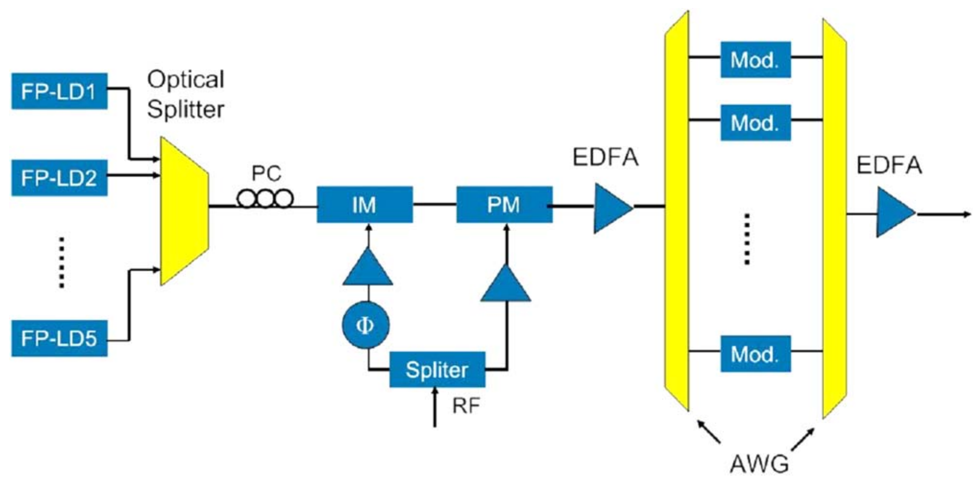


**Figure 6** The 110-channel extendable super-dense WDM light source scheme. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The feature of central wavelength versus different driving current of the WDM light source is also investigated, as shown in Figure 5. The linear fitting curse shows that the central wavelength can be changed precisely by carefully tuning the driving current, which can be used to match the WDM channels. Besides, the stability of the wavelength and power from each channel primarily relies on strict power supply and temperature control.

Figure 6 shows a 110-channel extendable high-dense WDM light source scheme. Five FP-LDs sequentially with central wavelength spacing of about 1.76 nm (about 220 GHz spacing at 1550 nm waveband) are used to provide seed carriers. The optical beams are gathered by an optical splitter. Then the seed carriers are mixing-modulated to generate 10-GHz spaced 110 channels (1100 GHz in total wave-range) by introducing 10.0 GHz RF. Through an EDFA as the preamplifier, the 110 optical carriers are separated by an AWG. The driving current of the FP-LDs should be tuned carefully, that the wavelengths can match the AWG channels. Each separated channel are modulated with unshared signals and then gathered by another AWG. The used AWGs should have 10-GHz channel spacing. Through another EDFA as the postamplifier, the 110 carriers with signals can be transmitted out by a long single-mode fiber. Obviously, this scheme is extendable using more FP-LDs and AWGs with high-dense channels. This scheme is expected to be widely used in future optical access network.

## 4. CONCLUSION

A scheme of high-dense WDM light source based on external mixing-modulated FP-LDs was investigated. A 10-GHz spaced 22-channel optical carrier supply module (OCSM) was achieved by cascading a multiple-longitudinal-mode FP-LD with two types of external modulators. Then the linear relationship between wavelength and driving current was verified and can be used to tune the central wavelength of an OCSM to match the AWG channels. Furthermore, a 110-channel extendable light source scheme was proposed. We believe that this scheme is potential in future optical access network.

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# A RECONFIGURABLE MOBILE ANTENNA FOR MULTIBAND OPERATION USING PIN-DIODE


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**ABSTRACT:** *This article proposes a mobile embedded antenna having tunable capacitance, and the validity of the proposed solution has been proven through its design, fabrication, and measurement. The antenna can be applied to long-term evolution (LTE) and DCS/PCS/wideband code division multiple access bands that are currently being used. The 4G mobile service requires antennas to expand its bandwidth so that it can include the LTE band and other service bands. However, it is difficult to obtain the low-band frequency due to the limited space for antennas in terminals. The proposed antenna with a PIN-diode was added to a basic planar inverted-F antenna structure to satisfy the intended bandwidth through the ON/OFF characteristics of the PIN-diode. To meet this requirement, a PIN-diode (MA4P274–1279T) manufactured by MACOM, was used to make the operation frequency of the low-band tunable. The antenna was fabricated and then measured using the optimized parameters, and the results have been compared with the simulated results. The antenna satisfied the requirements for operation frequency and performance for both low-band and high-band frequencies. The measured performance of the antenna fabricated with the optimized parameters was analyzed and compared with the simulation results.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:406–409, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28860


**Key words:** *reconfigurable antenna; PIN-diode; long-term evolution; planar inverted-F antenna*

## 1. INTRODUCTION

Recently, market structure and corporate activities around the world have been swiftly changing in response to rapid growth in