Monolithic Image-Rejection Optoelectronic Up-Converters that Employ the MMIC Process

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***Abstract*—This paper presents very small 30-GHz-band monolithic image-rejection optoelectronic up-converters that employ the HEMT-MMIC process for the first time. MMIC HEMT optoelectronic mixers are characterized by their direct photodetection and nonlinear characteristics. It is shown that common-source configurations have higher response than common-drain configurations, and up-converter applications are preferable to down-converter applications based on the HEMT direct photodetection characteristics. These characteristics are used to realize 30-GHz-band monolithic image-rejection optoelectronic up-converters. An in-phase divider and a branch-line hybrid with two HEMT optoelectronic mixers are successfully integrated into an MMIC chip with an area of 1.5 mm × 1.1 mm. Fundamental performance is demonstrated and excellent wideband performance, which comes from the well-balanced operation of monolithic integrated circuits, is confirmed. These monolithic optoelectronic mixers promise to realize compact and cost-effective 1-chip optical receivers for fiber optic links which support millimeter-waves.**

Introduction

FIBER optic distributed networks are very attractive for applications such as mobile radio communication systems [1]. Since a large number of radio base stations are required, hardware size and cost reduction is the key to realizing such systems [1]. Furthermore, the RF frequency must be increased to transmit a large number of subcarriers because transmission capability is limited by RF frequency bands. To meet these requirements simultaneously, the radio base stations (optical transceivers) must not only operate in the high-frequency bands, e.g., millimeter-wave bands, but also be realized as monolithic integrated circuits owing to their ability to realize compact and cost-effective hardware.

In the down link for such systems, it is sufficient to radiate millimeter-wave carrier signals at the radio base station regardless of the frequency of the subcarrier signals transmitted over the optical fiber. In the millimeter-wave mixing configuration [1], relatively low frequencies are utilized as subcarrier signals. After detection, they are up-converted to millimeter-waves by electrical mixers housed in the radio base station. In the up link for such systems, no high-frequency transmission is required [1]. Therefore, the hardware can be configured using the same LO oscillator for the down link and millimeter-wave down-converters. Unlike the millimeter-wave subcarrier transmission link configuration, this enables us to utilize cost-effective optical devices.

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Although additional components are required for such configurations, optoelectronic mixing [2], [3] allows us to eliminate the electric mixer. Furthermore, functional fiber optic link configurations, utilizing the combination of microwave functional components and optical devices (optoelectronic mixers) proposed by the authors, allow us to suppress undesired spurious frequencies without using microwave filters [4], [5]. However, a large number of components are still required, and their demonstrated bandwidths are narrow owing to the hybrid constitution of the discrete devices employed. Therefore, monolithic integration is indispensable.

As regards integration, electrical integration circuit technologies represented by MMIC's have recently been significantly improved [6]. Since the components required for optical receivers (except optical detectors) are micro-/millimeter-wave components, the optical detection [7], [8] and optoelectronic mixing [9]–[13] characteristics of MMIC compatible devices, e.g., MESFET's and HEMT's have been investigated to achieve monolithic integrated optical receivers. OEIC's [14] are possible alternatives. However, despite their many potential advantages, OEIC's have yet to outperform HIC's because of their complicated fabrication process.

This paper presents very small 30-GHz-band monolithic image-rejection optoelectronic up-converters that employ the HEMT-MMIC process, by adapting the idea of functional optical receivers [4], [5] for the first time. First, the new configuration and its principle is described. Second, MMIC HEMT optoelectronic mixers are characterized as regards direct photodetection and nonlinear characteristics in both common-source and common-drain configurations. Finally, the design and performance of monolithic image-rejection optoelectronic up-converters are discussed. The well-balanced operation of the monolithic image-rejection optoelectronic up-converter is successfully demonstrated.

Configuration and Principle

The configuration of the monolithic image-rejection optoelectronic up-converter, as well as the local oscillator and the optical transmitter [4], [5], are shown in Fig. 1.

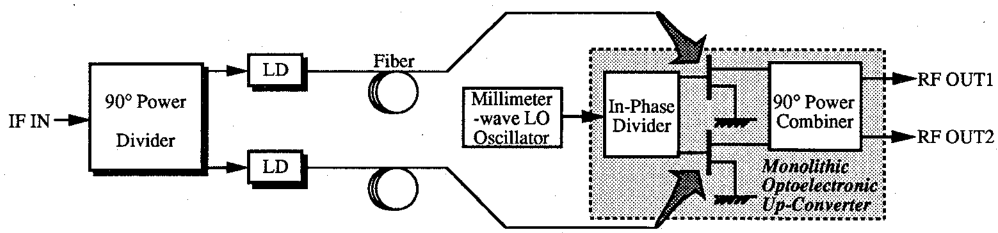


Fig. 1. Configuration of monolithic image-rejection optoelectronic up-converters, local oscillator, and optical transmitter.

This configuration eliminates the image frequencies at RF output ports without using filters. The optical transmitter, i.e., the 90° power divider, two laser diodes, and two optical fibers, are utilized to obtain two intensity-modulated optical signals with a microwave phase difference of 90°. Two HEMT optoelectronic mixers are illuminated separately by these two optical signals, and simultaneously electrical local frequencies are supplied in-phase to each gate terminal of the HEMT. The up-/down-converted frequencies are generated by mixing the detected optical signals and local signals through the nonlinearity of the HEMT [9]–[13]. Fig. 2 shows the HEMT optoelectronic mixing principle. Since the two RF frequencies generated have a phase difference of 90°, they are divided by the 90-degree-phase combination.

The key to achieving good fiber optic link performance is to assure the uniformity of both the optical path and optical receivers (each optoelectronic mixer as well as the passive components). The optical path can be made uniform by using such means as wavelength multiplex techniques. In this configuration, the uniformity of optoelectronic mixers is critical since they are utilized for both optical detection and mixing. Therefore, monolithic integration of the optical receiver is expected to achieve better performance than the hybrids that use photodiodes as optoelectronic mixers [4], [5]. Monolithic optoelectronic mixers based on MMIC's have the following advantages:

1) They simplify optical receiver configurations which utilize electric mixers as up-/down-converters.

2) Since IF or RF frequencies are supplied by optical illumination, microwave input circuits for such frequencies are not required and perfect LO to IF or RF isolation is assured.

3) Since MMIC compatible devices are, unlike photodiodes, three-port devices, no additional microwave components, which separate incident local signals and reflected signals, are required [4], [5].

4) If optoelectronic mixers are utilized as up-converters, the bandwidth of fiber optic links can be extended by using commercially available optical devices [2]–[5], and full monolithic optical receivers can easily be achieved owing to the absence of IF-band circuits in the receiver (see Fig. 1).

5) It is easy to integrate not only microwave passive components but also active components such as amplifiers and oscillators [6], thus producing compact and cost-effective 1-chip optical receivers.

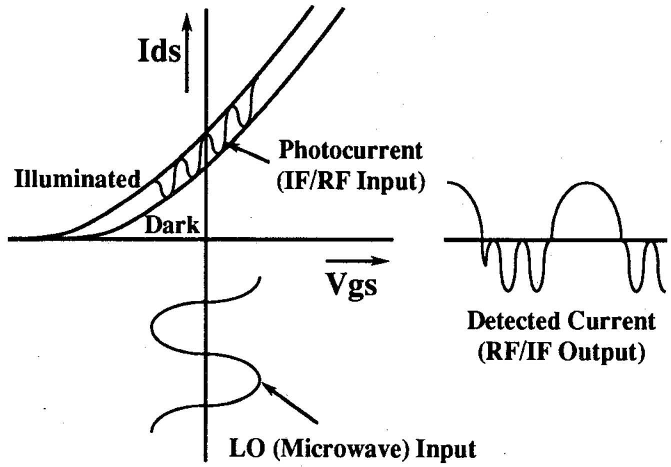


Fig. 2. Schematic expression of HEMT optoelectronic mixing. The photogenerated carriers contribute to the increase in *Ids*. This means that *Ids* is modulated by the modulation frequency, e.g., the subcarrier frequency of the optical carrier.

6) Well-balanced operation is easily obtained by closely spacing transistors on the semiconductor substrate.

HEMT Optoelectronic Mixing

HEMT optoelectronic mixing, shown in Fig. 2, is the result of both HEMT photodetection and nonlinear characteristics. Although the optoelectronic mixing characteristics of MMIC compatible devices, e.g., MESFET's and HEMT's, have been reported [9]–[12], most were discrete devices with common-source (CS) configuration, and no study has been made with respect to other integrated configurations. In MMIC's, such devices are easily configured in other configurations, i.e., common-drain (CD) or common-gate (CG). Therefore, the configurations' optoelectronic mixing performance must be clarified. CS and CD configurations are investigated since they have almost the same nonlinear performance [15].

MMIC HEMT optoelectronic mixers are characterized by using a modified electrooptic on-wafer probe station [8] as shown in Fig. 3. The HEMT's [8], whose cutoff frequency is approximately 40 GHz, whose gate length is 0.25 μm and whose gate width is 100 μm, are utilized to form monolithic integrated CS and CD HEMT optoelectronic mixers. The Ortel 3210C optical transmitter, whose optical wavelength is 0.85 μm and whose 3-dB bandwidth is 10 GHz, is utilized as the optical source/intensity-modulator. Optical power is coupled to the HEMT's via multi-

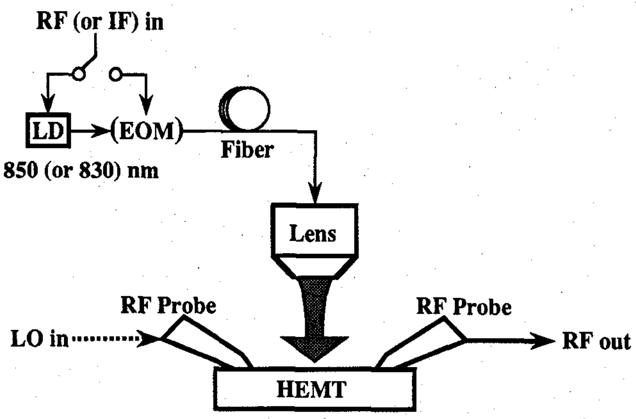


Fig. 3. Experimental setup for on-wafer electrooptic measurement.

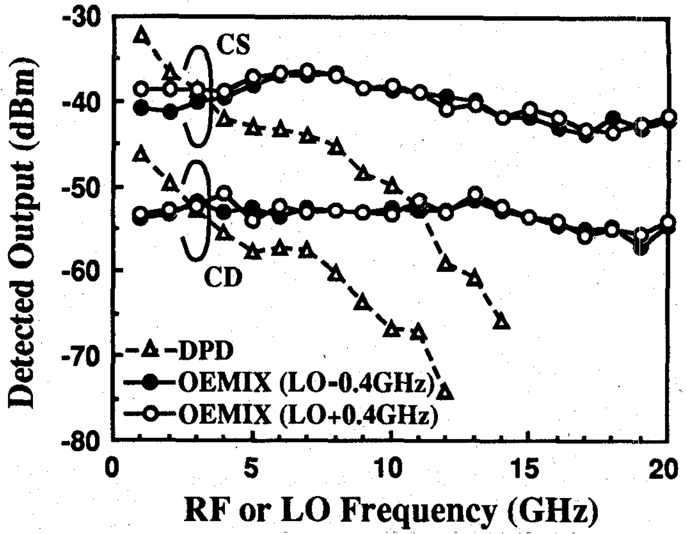


Fig. 4. Measured direct photodetection (DPD) and optoelectronic mixing (OEMIX) LO frequency response of MMIC HEMT with both common-source (CS) and common-drain (CD) configurations. For OEMIX measurements, LO input power is −4 dBm and IF frequency is 0.4 GHz. In all measurements, electrical power supplied to laser diodes is 10 dBm, the optical spot diameter is 10 μm, and the illuminated dc power is 0.64 mW.

mode fibers and lenses [8]. The optical spot diameter is approximately 10 μm and the illuminated dc power is 0.64 mW. The input power supplied to the optical transmitter was 10 dBm for all measurements. During the optoelectronic mixing measurements, electrical LO power was supplied to the gate terminal, and detected output power was extracted from the drain/source terminals for CS and CD configurations, respectively.

Fig. 4 shows the direct photodetection (DPD) and optoelectronic mixing (OEMIX) response of the MMIC HEMT's as a function of RF and LO frequency (at IF frequency of 0.4 GHz), respectively, with CS and CD configurations. DPD performance decreases as frequency increases while OEMIX has almost flat LO frequency response. It is shown that HEMT OEMIX enables us to extend the fiber optic link bandwidth by using high-speed (millimeter-wave) electric devices and low-speed (commercially available) optical devices. As also shown in this figure, CS yields higher response than CD by 10–15 dB up to 20 GHz, and this superiority is almost the same for both DPD and OEMIX. Since both CS and CD have nearly equal nonlinearity [15], the difference is determined by their direct photodetection performance. Fig. 5 shows CS MMIC HEMT's DPD performance and OEMIX IF frequency response at an LO frequency of 10 GHz. Both frequency responses are quite similar, and both decrease as frequency increases. Taking into account the above results, the HEMT's optoelectronic mixing performance is mostly determined by the direct photodetection characteristics. HEMT's direct photodetection has high responsivity at lower frequencies owing to the device's internal gain and its photoconductive behavior [8], [12]. Therefore, up-converter application of HEMT optoelectronic mixers is more desirable than down-converter application as regards the increase in fiber optic link response for restricted-bandwidth microwave transmission. As described above, millimeter-wave MMIC's such as amplifiers and oscillators can be easily achieved [6], thus realizing 1-chip optical receivers which support millimeter-wave carrier signals by adapting MMIC optoelectronic up-converters. Furthermore, the common-source (CS) configuration is preferable to the common-drain (CD) configuration due to its higher response. The difference of OEMIX performance with the CS and CD configurations is thought to come from the difference in Cgs deviation influence on both configurations [16].

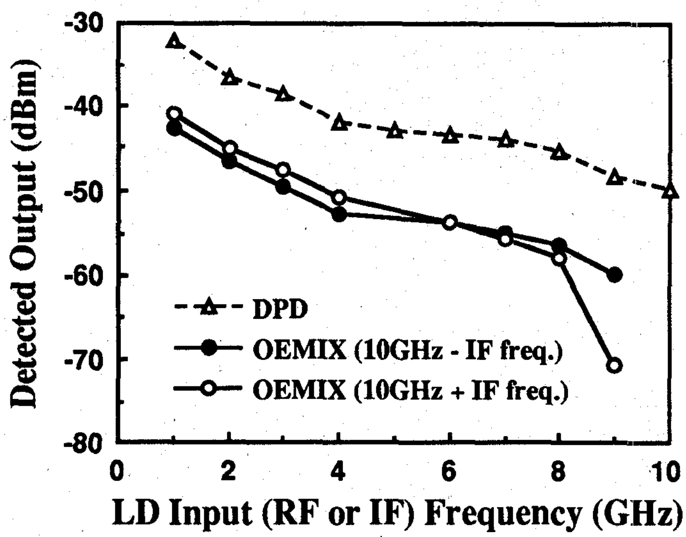
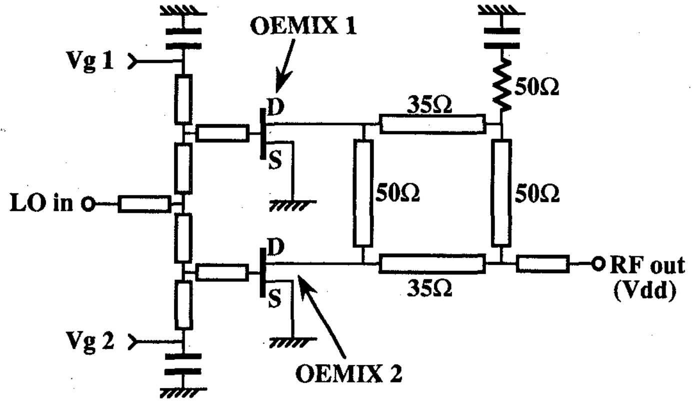


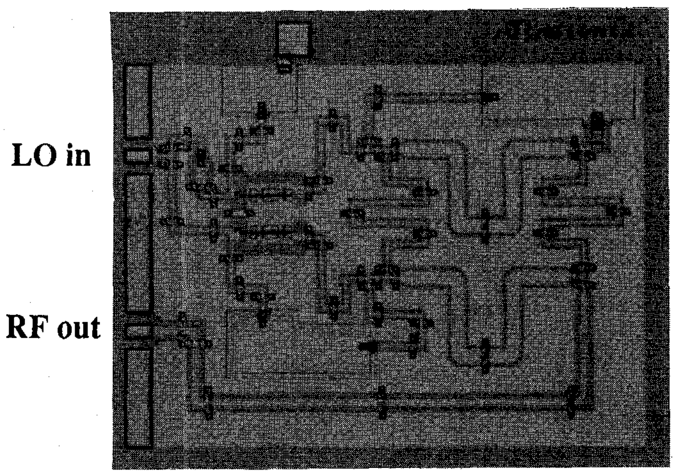
Fig. 5. Measured direct photodetection (DPD) and optoelectronic mixing (OEMIX) IF frequency response of MMIC HEMT with common-source (CS) configuration. For OEMIX measurements, LO input power is −4 dBm and LO frequency is 10 GHz. In all measurements, electrical power supplied to laser diodes is 10 dBm, the optical spot diameter is 10 μm and the illuminated dc power is 0.64 mW.

Monolithic Image-Rejection Optoelectronic Up-Converters

30-GHz-band monolithic image-rejection optoelectronic up-converters were designed, and fabricated using the HEMT-MMIC process. Fig. 6 shows the circuit dia-



(a)



(b)

Fig. 6. Circuit diagram and photomicrograph of the monolithic image-rejection optoelectronic up-converter. (a) Circuit diagram. (b) Photomicrograph. Chip size: 1.5 × 1.1 mm.

gram and photomicrograph of the fabricated circuit. The chip size is 1.5 mm × 1.1 mm. Two HEMT's [8], whose gate width was 100 μm, were utilized to form the optoelectronic mixers. The common-source configuration was exploited to increase the optoelectronic mixing response. The gap between the two HEMT's is approximately 100 μm. Coplanar waveguides (CPW's) parallel-T junctions and 30-GHz-band branch-line hybrids consisting of 35-Ω and 50-Ω CPW's were utilized as LO in-phase dividers and RF 90° combiners, respectively. One of the output ports of this branch-line hybrid is terminated by a 50-Ω resistor for on-wafer measurement. In the design, commercially available CAD software (Touchstone) was used only to optimize the values of lumped elements and coplanar waveguide line lengths. The chip size can be reduced by using thin film microstrip (TFMS) lines [17] as transmission lines instead of CPW's.

First, each HEMT optoelectronic mixer (OEMIX1 and OEMIX2) integrated in the monolithic image-rejection optoelectronic up-converters was investigated to confirm uniform optoelectronic mixing performance. A modified electrooptic on-wafer probe station, a 0.83-μm LD, and $LiNbO_3$ external optical modulator [8] were utilized for this measurement as shown in Fig. 3. The optical spot diameter was approximately 20 μm, and the illuminated dc power was 0.4 mW. Fig. 7 shows measured gate bias ($Vg1$ and $Vg2$) dependence of each optoelectronic mixer at the LO frequency of 30 GHz and LO input power of 0 dBm. The IF frequency was 0.4 GHz and IF input power was 10 dBm. The drain bias (Vdd), supplied through a wideband bias and on-wafer probes attached to the RF output port, was 2 V, and unilluminated HEMT gate bias was -1.2 V. Both HEMT optoelectronic mixers have nearly equal characteristics especially when Vg is less than -0.4 V, thus confirming well-balanced operation from the image-rejection optoelectronic mixers.

The monolithic image-rejection optoelectronic up-converters were tested in the experimental setup shown in Fig. 1, by using Cascade Microtech microwave and lightwave on-wafer probes. Two laser diodes (Mitsubishi FU-01SLD, $\lambda = 0.85$ μm), a 100-MHz-band 90° power divider, and two multi-mode fibers were utilized as the optical transmitter. Fig. 8 shows measured Current-Light-output (I–L) and Intensity-Modulation/Direct-Detection (IM/DD, at 1 GHz, 10 dBm input, using identical fiber and photodetector) performance of the two laser diodes. Both laser diodes have almost the same characteristics. Fig. 9 shows measured performance of the 100-MHz-band 90° power divider. The phase and magnitude errors are less than 2° and 2 dB, respectively, in the frequency range 85–155 MHz.

Each active region of the two HEMT optoelectronic mixers was illuminated through two lightwave on-wafer probes. The optical output power of each laser diode was set to approximately 3 mW ($I = 24$ mA shown in Fig. 8), and the position of each lightwave on-wafer probe was adjusted to obtain equal IM/DD performance at the identical bias condition ($Vdd = 2$ V, $Vg = 0$ V), since the optical spot diameter cannot be specified. The adjusted IM/DD performance is -37 dBm (at 0.4 GHz, 10 dBm input). Therefore, the effective illuminated optical dc power is assumed to be about 0.2 mW for a 20-μm optical spot [8]. In the measurement, Vdd is set to 2 V and gate biases ($Vg1$ and $Vg2$) are set near the pinch-off voltages to achieve well-balanced operation as shown in Fig. 7.

Fig. 10 shows the measured RF (upper sideband) and image (lower sideband) frequency output power versus the LO frequencies at an LO input power of 4 dBm, an IF input power of 16 dBm, and an IF frequency of 110 MHz. Millimeter-waves (30 GHz-band frequencies) are successfully obtained at the monolithic integrated optical receiver. Furthermore, in the LO frequency range of 29.2–31.2 GHz, image rejection of better than 15 dB is achieved. Fig. 11 shows LO input power dependence of both RF and image frequencies at an LO frequency of 30 GHz. Fig. 12 shows the measured return loss at the RF output port. A return loss of better than 15 dB is obtained over the RF frequency range of 27.0–33.7 GHz. Fig. 13 shows the IF frequency response at an LO frequency of 30 GHz and an IF input power of 16 dBm. Image rejection of better than 20 dB is obtained in the IF frequency range of 70–170 MHz.

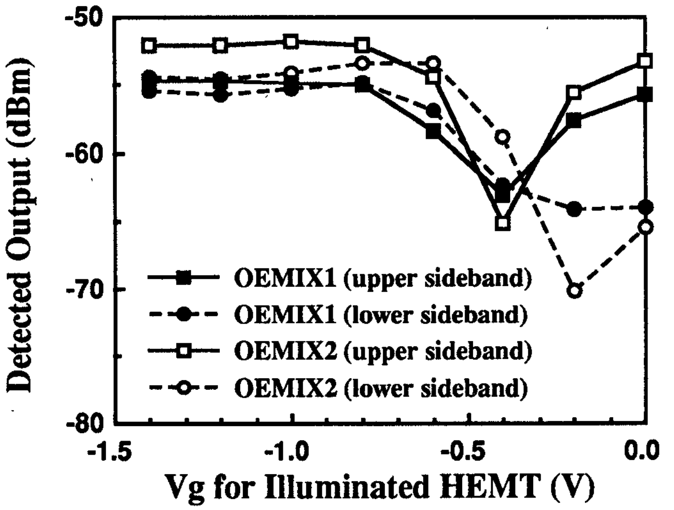


Fig. 7. Measured *Vg* dependence of each optoelectronic mixer (OEMIX1 and OEMIX2) integrated in the monolithic image-rejection optoelectronic up-converters at an LO frequency of 30 GHz and an LO input power of 0 dBm, and an IF frequency of 0.4 GHz and an IF input power of 10 dBm. The drain bias (*Vdd*) is 2 V, and unilluminated HEMT gate bias is −1.2 V. The optical spot diameter is 20 μm and the illuminated dc power is 0.4 mW.

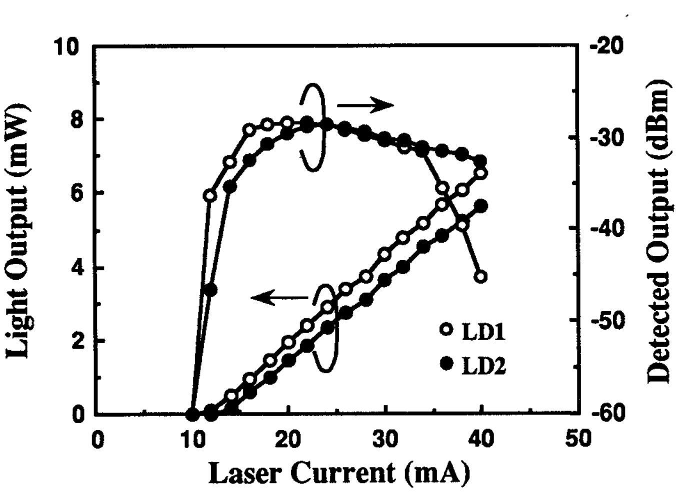


Fig. 8. Measured current–light-output (I–L) and IM/DD (at 1 GHz, 10 dBm input, using identical fiber and photodetector) performance of two laser diodes (LD1 and LD2).

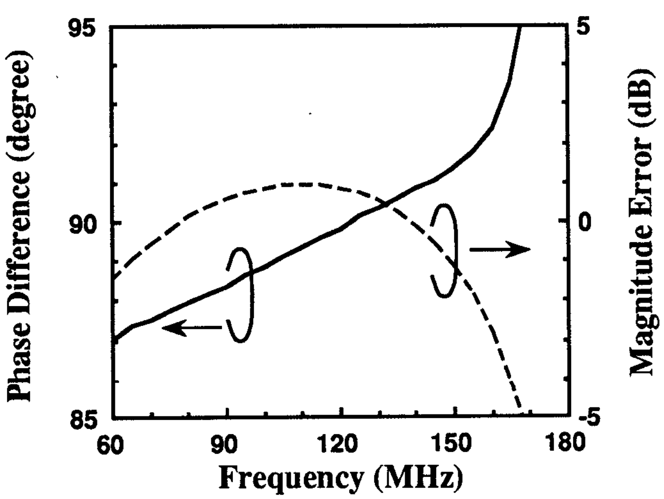


Fig. 9. Measured performance of the 100-MHz-band 90° power divider. Solid line represents phase difference and dashed line represents magnitude error.

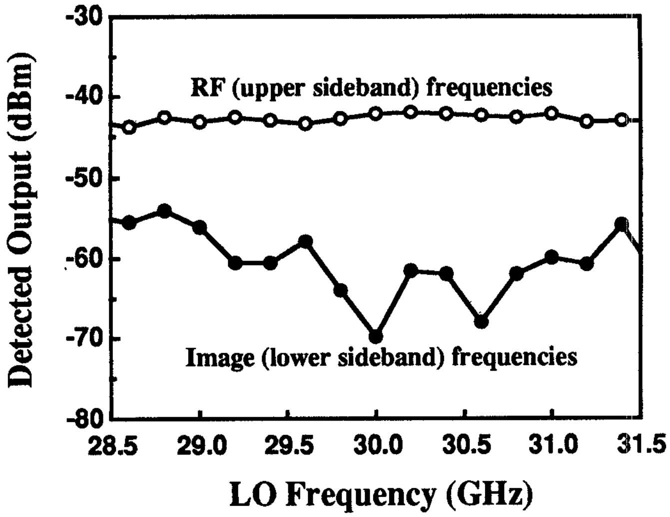


Fig. 10. Measured RF (upper sideband) and image (lower sideband) frequency output power versus the LO frequencies at an LO input power of 4 dBm, an IF input power of 16 dBm, and an IF frequency of 110 MHz.

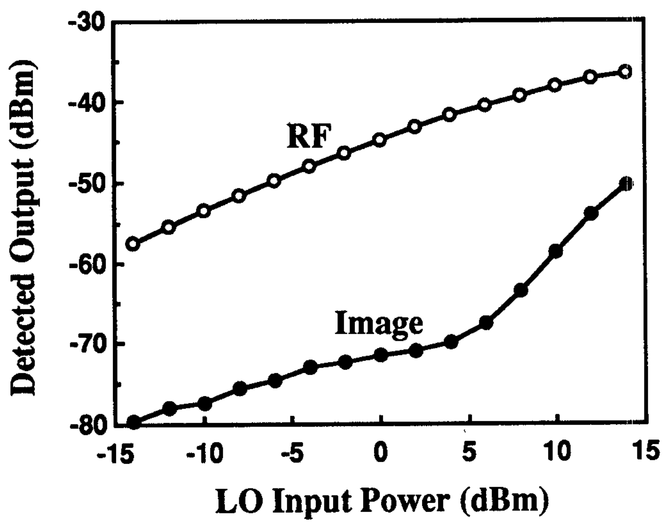


Fig. 11. LO input power dependence of both RF and image frequencies at an LO frequency of 30 GHz, an IF frequency of 110 MHz, and an IF input power of 16 dBm.

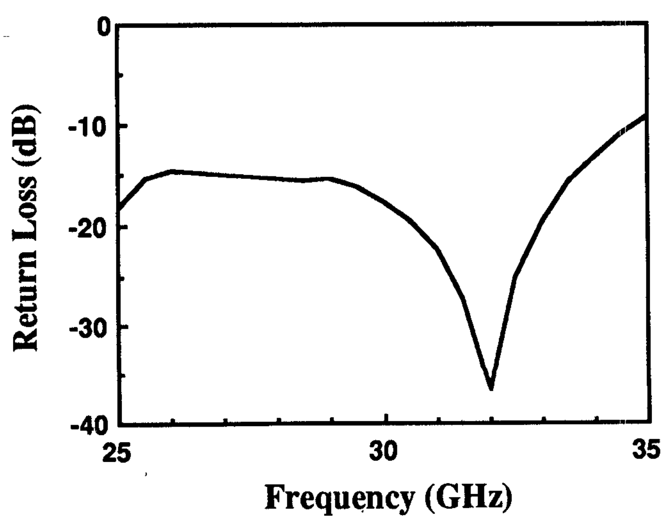


Fig. 12. Measured return loss at the RF output port.

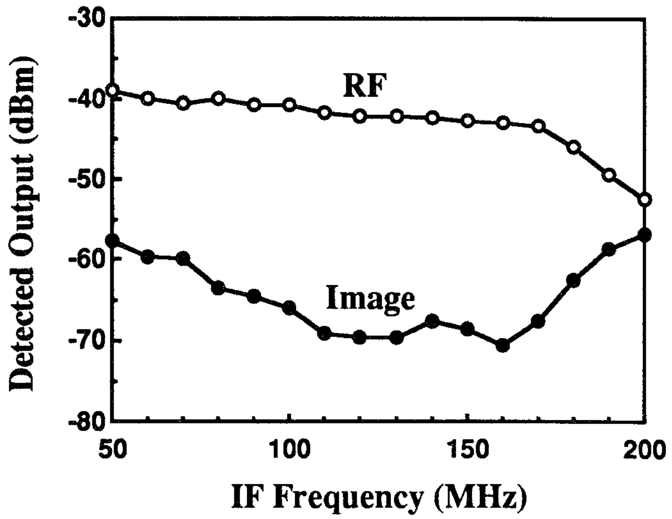


Fig. 13. IF frequency response at an LO frequency of 30 GHz, LO input power of 4 dBm, and IF input power of 16 dBm.

Discussion

In the image-rejection microwave mixers, perfect image rejection is realized if the conversion losses and phase shifts in the mixers are identical, and the phase and amplitude balances of the passive components are complete. The image rejection is determined as a function of overall amplitude and phase imbalance [18]

$$R_I = -10 \cdot \log \left[\frac{1 - 2\sqrt{G}\cos\theta + G}{1 + 2\sqrt{G}\cos\theta + G} \right]$$

where θ is the phase imbalance and G is the gain imbalance. For example, achieving 20 dB image rejection requires that the phase error be kept below 10° and the gain imbalance below 1 dB. In the optoelectronic mixer, photodetection functions are added to the mixer itself. Therefore, photodetection imbalances of optoelectronic mixers directly degrade their performance even if their mixing conversion is the same as shown in Figs. 4 and 5.

In the hybrids utilizing discrete devices [4], [5], it is very difficult to achieve the well-balanced operation, not only as regards mixing conversion but also photodetection characteristics. Furthermore, the imbalance of passive components as well as connection length between components is also critical especially in the high-frequency range such as millimeter-waves. Furthermore, in the optical receiver utilizing photodiodes as optoelectronic mixers, additional microwave components such as circulators are required [4], [5], thus making it difficult not only to assure the well-balanced operation but also to simplify the hardware. Therefore, the monolithic integration approach is the only way to realize the well-balanced operation of the proposed optical receivers shown in Fig. 1.

The monolithic image-rejection optoelectronic up-converter has achieved image rejection of better than 20 dB over the operating frequency range of the IF-band 90° power divider as shown in Fig. 13. This means that, in the monolithic integrated circuits, nearly perfect well-balanced operation has been realized. In addition, MMIC compatible devices, i.e., transistors, are three-port devices unlike photodiodes, thus having inherent advantage for mixer applications. This advantage, as well as employing the MMIC process, is successfully utilized to form very small monolithic optoelectronic up-converters with a chip area of 1.5 mm × 1.1 mm.

The imbalance of each laser diode and optical path also degrades the fiber optic link performance discussed here. Laser diodes could be made uniform by utilizing monolithic integrated circuit techniques as demonstrated in this paper. The optical path can be made uniform by using optical multiplex techniques, e.g., the wavelength multiplex technique. Although 0.8-μm-band optical carriers are utilized in this paper, the techniques described herein can be easily adapted to support 1.3 or 1.55 μm optical carriers by choosing a different device material such as InP. Furthermore, by utilizing MMIC miniaturization techniques such as line-unified FET [19] or multilayer MMIC structures [17], multifunction monolithic optoelectronic mixers such as the balanced type could be realized with a significant size reduction.

Conclusion

This paper has presented very small 30-GHz-band monolithic image-rejection optoelectronic up-converters that employ the HEMT-MMIC process for the first time. Excellent wideband performance, unlike hybrid constitution of discrete devices, has been successfully demonstrated in accordance with predicted results. This comes from the well-balanced operation of monolithic integrated circuits. In particular, millimeter-waves (30 GHz-band frequencies) have been successfully obtained at the monolithic integrated optical receiver. This optical receiver configuration allows us to easily integrate millimeter-wave amplifiers and oscillators. Therefore, the proposed monolithic optoelectronic mixers promise to realize compact and cost-effective 1-chip optical receivers for fiber optic links which support millimeter-waves.

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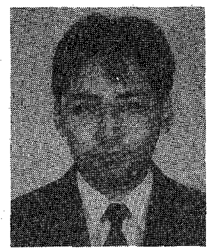

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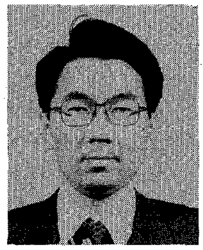

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