BROADBAND WILKINSON BALUN USING PURE LEFT-HANDED TRANSMISSION LINE

Young-Ho Ryu,[1] Jae-Hyun Park,[2] Jeong-Hae Lee,[2] and Heung-Sik Tae[1]
[1] School of Electrical Engineering and Computer Science, Kyungpook National University, Korea
[2] Department of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea; Corresponding author: jeonglee@hongik.ac.kr

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ABSTRACT: *Utilizing the opposite phase shift property of a microstrip line (MSL) and a pure left-handed transmission line (PLH TL), the broadband Wilkinson balun is designed. The PLH TL without a right-handed (RH) branch is designed using effectively negative elements obtained by a cross connection of vias to ground. The PLH TL gives inherently phase-advanced response properties because of negative phase velocity, whereas a conventional MSL has a phase-lag response. The property of a broadband left-handed branch of a PLH TL applies to the implementation of broadband balun. The proposed balun has a good return loss, a good isolation between output ports, an equal-power division, and a 180° ± 10° phase difference in a wide fractional bandwidth of ~71%. Furthermore, the wideband balun that has the fractional bandwidth of 107.8% is theoretically designed with the modified PLH TL having four unit cells.* Microwave Opt Technol Lett 52: 1665–1668, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25242

Key words: *metamaterial; pure left handed transmission line; balun*

1. INTRODUCTION

A balun, as a 3-port device, converts an unbalanced single-ended signal into a balanced two-ended signal with equal transmission coefficients. It is generally used for feeding networks of two-wire antennas, which require balanced current on each branch to maintain symmetrical radiation patterns. These baluns are also required for image rejection mixers, balanced mixers, balanced modulators, push-pull amplifiers, and so on. Generally, the printed baluns have been designed using a distributed TL or lumped elements. Distributed TL baluns are inherently narrow band because of the frequency dependence of a phase constant. Also, lumped element baluns have compact size and can easily be integrated. However, they also have narrow band because of a narrow band differential output phase [1, 2]. To overcome the above shortages of the baluns, the broadband baluns were implemented using the novel concept of composite right/left transmission lines (CRLH TLs) [3, 4]. These CRLH TL baluns [3, 4] utilize RH and LH transmission branches, simultaneously, to obtain a broad operating bandwidth. Thus, in the design process of a balun, the closed stop band condition so-called balanced condition [5] of CRLH TLs must be required because the continuity of the phase of CRLH TL should be satisfied.

In this letter, a broadband Wilkinson balun is designed using a conventional microstrip line (MSL) and a pure left-handed transmission line (PLH TL) [6]. The PLH TL without a RH band is realized by a cross connection circuit using only distributed structures, such as a defected ground structure (DGS), a wire bonded interdigital capacitor (WBIDC), and vias. The slope of the phase-response curve for the PLH TL can be flexibly controlled in the broad frequency range because the PLH TL has the capability of arbitrarily synthesizing the transmission phase response and can be realized as a phase-adjusting TL. The above properties of the PLH TL apply to the implementation of a broadband balun. In the design process of a PLH TL balun, the balanced condition is not required because the PLH TLs have only LH transmission branch. In addition, a PLH TL with wide LH band can be easily designed by some transformations of the structure. Its LH bandwidth can also be controlled more easily than that of CRLH TL [6].

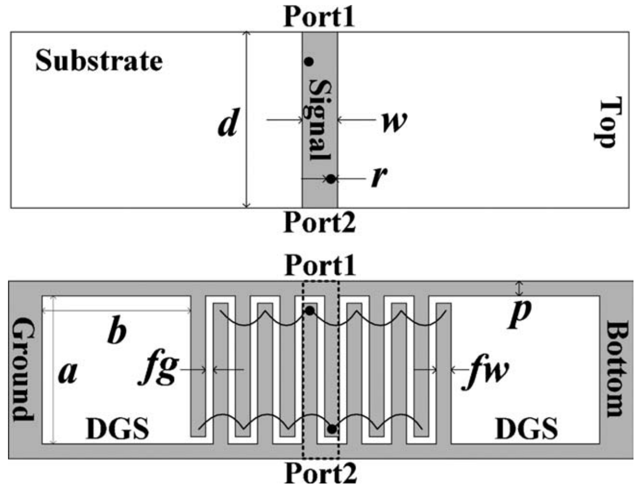


Figure 1 Unit-cell structure of PLH TL (a = b = 5 mm, w = 1.1 mm, f_g = 0.1 mm, f_w = 0.5 mm, r = 0.3 mm, p = 0.1 mm, the number of finger pairs = 6, unit cell length (d) = 5.2 mm)

2. PURE LEFT-HANDED TRANSMISSION LINE

Figure 1 shows the unit-cell structure of a PLH TL. The unit cell consists of a DGS with a WBIDC, two vias, and a MSL. To realize the PLH TL, the signal line is cross connected to the end of each finger of the WBIDC in the ground plane by vias as shown in Figure 1. The via near the port 1 of a signal line is connected to the ground plane which links to port 2 and vice versa. Thus, the circuit model of a unit cell is exactly represented by a 4-terminal network with cross-connected circuit as shown in Figure 2. In Figure 2, the DGS is equivalently modeled as a parallel resonant circuit with the capacitance (C_d) and inductance (L_d). The inductance (L_{t1}) is determined by the length of the signal line between the vias. Also, the capacitance (C_t) and inductance (L_t) of the host TL are parasitic elements of the PLH TL. The cross-connected part in Figure 2(a) can be directly converted to T-equivalent circuit with impedance (Z) and admittance (Y) and common ground as shown in Figure 2(b) using the rearrangement of the circuit and r-parameter analysis [7]. Then, the impedance (Z) and admittance (Y) are expressed as the following

$$Z = r_{11} - r_{12} = r_{22} - r_{21} = 2 \times \frac{Z_1 Z_2}{Z_1 + Z_2} = \frac{2\omega^2 L_{t1} L_d}{j\omega(\omega^2 C_d L_{t1} L_d - L_{t1} -_d)} \quad (1)$$

$$Y = 1/r_{12} = -\frac{Z_1 + Z_2}{Z_1 Z_2} = -\frac{j\omega(\omega^2 C_d L_{t1} L_d - L_{t1} - L_d)}{\omega^2 L_{t1} L_d} = \frac{j\omega(\omega^2(-C_d)(-L_{t1})(-L_d) - (-L_{t1}) - (-L_d))}{\omega^2(-L_{t1})(-L_d)} \quad (2)$$

where $Z_1 = j\omega L_{t1}$ and $Z_2 = \frac{j\omega L_d}{1-\omega^2 C_d L_d}$.

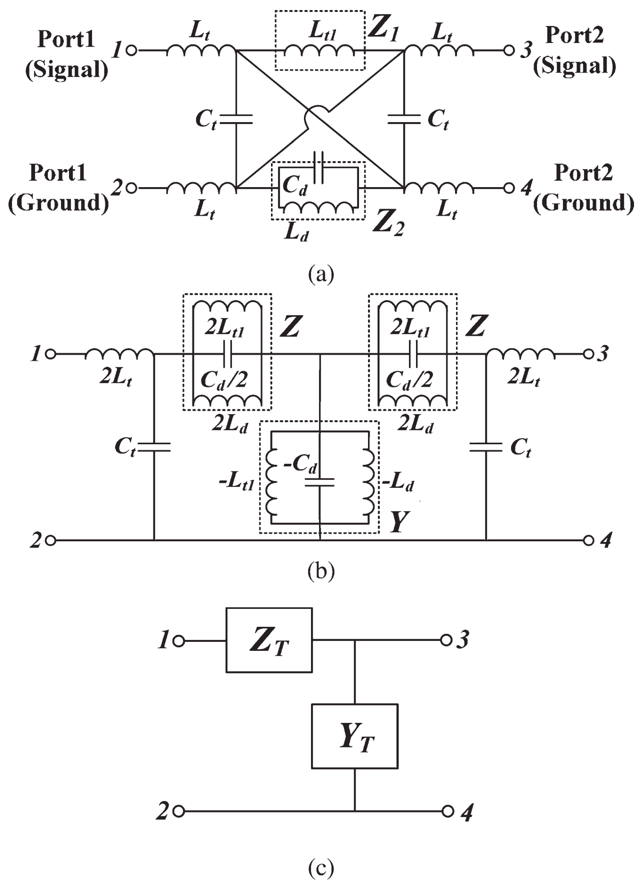


Figure 2 Equivalent circuits: (a) Original 4-terminal network; (b) Modified 3-terminal network with common ground (c) Ladder-network

It is noted that the admittance value(Y) corresponding to effective epsilon has the negative values of parallel composition of Z_1 and Z_2. There is only one choice that all elements of the admittance must have negative values as shown in [Fig. 2(b)]. The modified equivalent circuit can be reduced to simple ladder-network by T-Π transformations [7] as shown in Figure 2(c). Then, the effective permeability and permittivity values are obtained from $\mu_{\rm eff} = Z_T(\omega)/j\omega d$ and $\varepsilon_{\rm eff} = Y_T(\omega)/j\omega d$ [5]. Consequently, The Im(Y_T) corresponding to an $\varepsilon_{\rm eff}$ monotonically decreases with negative sign [6], whereas that of a CRLH TL increases [5] as the frequency increases. The Im(Z_T) corresponding to $\mu_{\rm eff}$ obeysthe Lorentz shape like to CRLH TL of the conventional resonant type [8]. Therefore, the PLH TL has only the LH band without RH band in the reduced Brillouin zone (BZ) because $\varepsilon_{\rm eff}$ always have negative sign. It is noted that the reduced BZ is defined by $0 < \beta d < \pi$ where βd of π corresponds to half a guided wavelength on one dimensional structure. The circuit parameters of Figure 2 can be extracted by circuit and full-wave simulations (Ansoft's Designer and HFSS) as the following; $L_d = 4.57$ nH, $C_d = 8.20$ pF, $C_t = 0.24$ pF, $L_t = 0.28$ nH, and $L_{tl} = 1.36$ nH.

3. BROADBAND WILKINSON BALUN

3.1. Implementation

The PLH TL gives an inherently phase-advanced response because of the negative phase velocity, whereas a conventional MSL has a phase-lag response as shown in Figure 3. In other words, the dispersion curves of a PLH TL and a MSL show an opposite phase shifting property. Using this property, a broadband Wilkinson balun is designed. Figure 3 shows the phase response curves of a PLH TL and a MSL. The curves are obtained as follows:

$$\phi_p = \beta_p \times L_1 \text{ and } \phi_M = \beta_M \times L_2. \tag{3}$$

where $\beta_{\rm p}$ and $\beta_{\rm M}$ are phase constants of the PLH TL and the MSL and $\phi_{\rm p}$ and $\phi_{\rm M}$ are phases with respect to the lengths (L_1, L_2) of each TL in Figure 4, respectively. To match the phase response with 180° phase difference between a PLH TL and a MSL and obtain a broad operating band at the two output ports of a designed balun, the slopes of their phase characteristics must be equal in the broad frequency range according to the following relation

$$\left.\frac{d\phi_P}{d\omega}\right|_{f_1\le f\le f_2} = \left.\frac{d\phi_M}{d\omega}\right|_{f_1\le f\le f_2}. \tag{4}$$

To satisfy the Eq. (4), the lengths of L_1 and L_2 are determined as 10.4 mm (corresponding to 2-stage PLH TL) and 41 mm, respectively. Then, the phase-response curve of the PLH TL can have the same slope as that of the MSL with a 180° ± 10° phase difference over the broad frequency range as shown in Figure 3. The ±10° bandwidth of a balun is determined by the frequencies of f_1 and f_2 where the following phase-responses are satisfied; $|\phi_{P1}| + \phi_{M1} - 360° = 180° \pm 10°$ and $|\phi_{P2}| + \phi_{M2} - 360° = 180° \pm 10°$, respectively.

Figure 4(a) shows the schematic diagram of the broadband Wilkinson balun. The proposed broadband balun is realized by a conventional Wilkinson power divider with two phase shift TLs, such as a PLH TL and a MSL. The center frequency of f_0 is set to be 2.5 GHz. The input feed line is implemented using a 50 Ω MSL with width of 0.6 mm and length of 3 mm. Two $\lambda/4$ MSL branches in the Wilkinson divider are implemented using 70.7 Ω MSLs with the following parameters; width of 0.26 mm and length of 11.8 mm. The unit-cell dimensions of the PLH TL are the same as those shown in Figure 1. The matching section between the PLH unit and the Wilkinson divider is employed as a 25 Ω MSL (width = 1.9 mm, length = 10.8 mm) because the characteristic impedance of the PLH TL is 12.5 Ω. To have the same phase slope with that of the PLH TL with a 180° phase difference, the dimensions of the MSL are set to be; width of 0.6 mm (50 Ω) and length of 64 mm ($L_2 + 23$ mm: 23 mm = $\lambda/4$ MSL × 2).

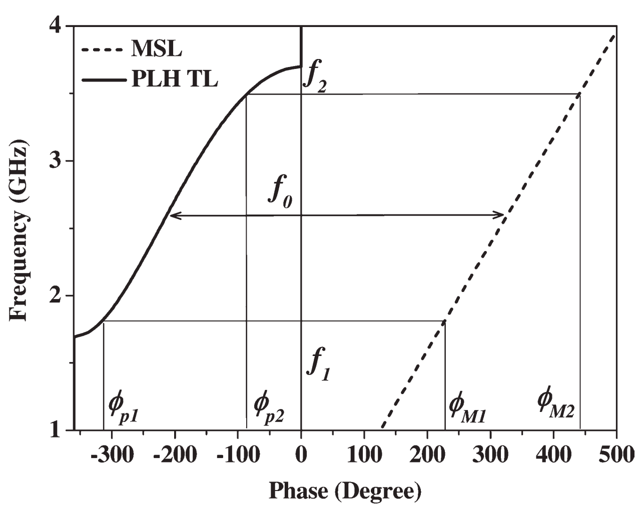
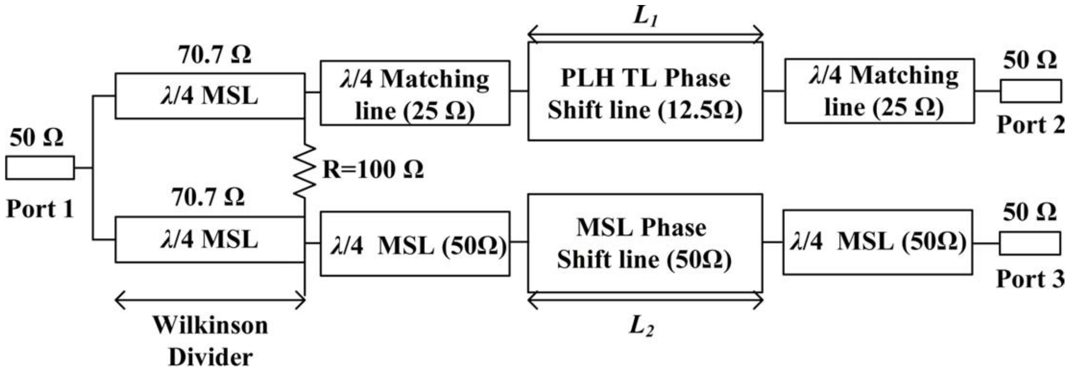
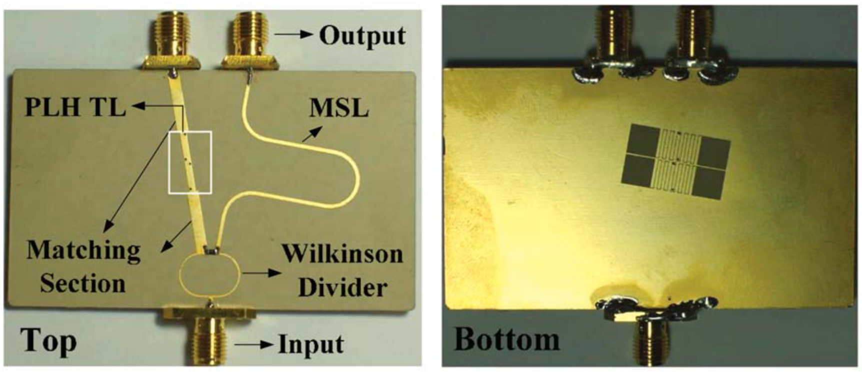


Figure 3 Phase response curves of the PLH TL and a MSL. ($\phi_p = \beta_p \times L_1,\ \phi_M = \beta_M \times L_2;\ L_1 = 10.4$ mm, $L_2 = 41$ mm)



(a)



(b)

Figure 4 (a) Schematic diagram of broadband Wilkinson balun; (b) Top and bottom views of fabricated broadband Wilkinson balun. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 4(b) shows the fabricated broadband Wilkinson balun. The balun is designed using a Rogers RO 3010 substrate with the relative permittivity (ε_r) of 10.2 and the height (h) of 0.64 mm. The input and output ports utilize 50 Ω coaxial connectors.

3.2. Simulated and Measured Results

Figure 5 shows the simulated and measured return loss of S_{11} at the port 1. The simulation tool is Ansoft's HFSS. The measured (simulated) return loss is below −11.5 dB (−13 dB) in the operating band from 1.47 GHz (1.44 GHz) to 3.09 GHz (2.99 GHz), indicating that the device is well matched. Figure 6 shows the simulated and measured isolation of S_{23} (or S_{32}), and the through of S_{21} and S_{31}. It is found that the good measured (simulated) isolation, especially at the center frequency of f_0 with a minimum value of −29.4 dB (−33.4 dB), and equal power division between two output ports are achieved as shown in Figure 6. The center frequency of f_0 in measurement is rather downshifted to 2.25 GHz because the conductor thickness of WBIDC is not considered in the simulation. The measured isolation remains below −13.8 dB in the operating range from 1.47 GHz to 3.09 GHz. At the center frequency, the measured (simulated) power through the output port 2 and 3 are −3.72 dB

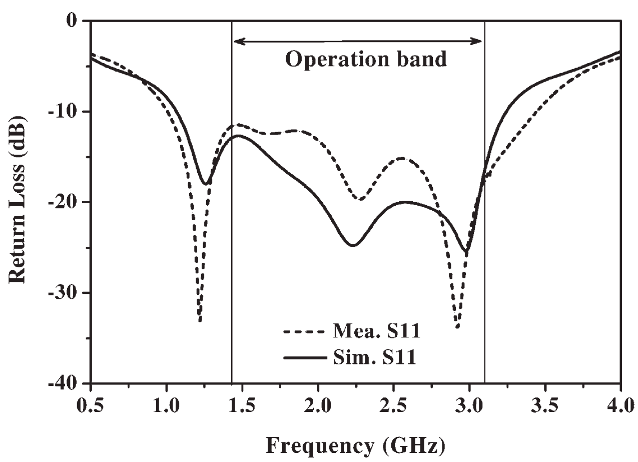


Figure 5 Simulated and measured return loss

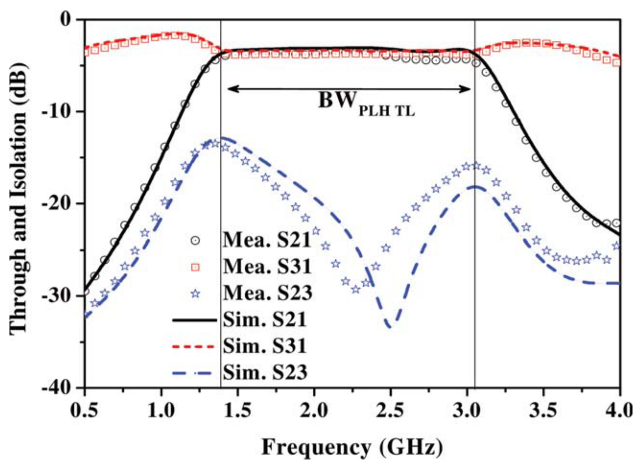


Figure 6 Isolation and through. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

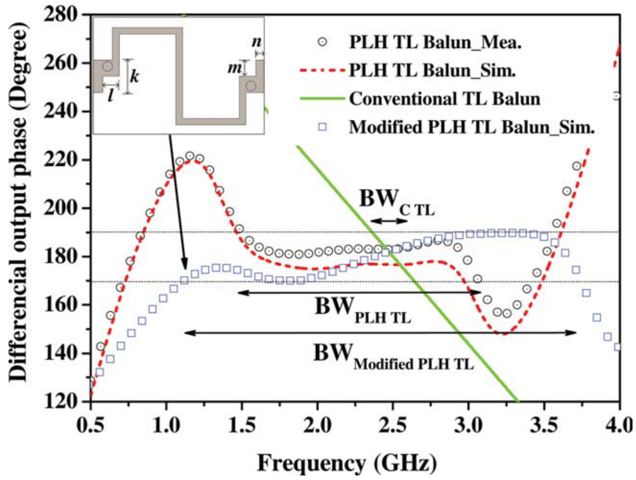


Figure 7 Differential phase between two output ports (Modified PLH TL: meander line-length = 8.6 mm, width = 0.2 mm, b = 7 mm, k = 0.6 mm, l = m = 0.5 mm, n = 0.3 mm, the number of finger pairs = 5). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

(−3.43 dB) and −3.43 dB (−3.2 dB), respectively. The maximum value of amplitude unbalance, the difference in power of S_{31} and S_{21} between two output ports, is measured (simulated) at 0.7 dB (0.35 dB) in the operating band.

Figure 7 shows the simulated and measured phase differences between two output ports. The simulated phase differences between two output ports of a conventional MSL Wilkinson balun are compared. The conventional MSL Wilkinson balun are designed using two branches of −90° and −270° phase shift MSL. The differential output phase is shown to be flat in the operation band of the proposed balun. The fractional 180° ± 10° bandwidth of the balun based on the PLH TL is measured (simulated) at 71% (70%) from 1.47 GHz (1.44 GHz) to 3.09 GHz (2.99 GHz), whereas the bandwidth of the conventional MSL balun is only 10.8% from 2.36 GHz to 2.63 GHz. Consequently, the broadband Wilkinson balun based on a PLH TL has good properties, such as return loss, isolation, and through in the broad frequency range.

Furthermore, a wideband balun based on modified PLH TL [6] having a wide LH bandwidth is designed by the full wave simulation. The illustration of Figure 7 shows the top view of the modified PLH TL. The other dimensions of modified PLH TL are exactly the same with those of Figure 1 except for dimensions in figure caption of Figure 7. In this case, to satisfy the Eq. (4), the lengths of L_1 and L_2 are determined as 20.8 mm (corresponding to 4-stage modified PLH TL) and 60.3 mm, respectively. The designed balun has the fractional bandwidth of 107.8% from 1.12GHz to 3.74GHz, as shown in Figure 7. Consequently, the PLH TL balun is well-suited for RF devices requiring a broadband balanced signal.

4. CONCLUSIONS

A broadband Wilkinson balun is designed using a PLH TL. The PLH TL gives inherently phase-advanced response because of a negative phase velocity. It has the capability of arbitrarily synthesizing the transmission phase response. The properties of the PLH TL apply to the implementation of broadband baluns. The balun has good return loss, good isolation, equal-power division, and a 180° phase difference between two output ports in the broad frequency range. The measured isolation remains below −13.8 dB and the return loss is below −11.5 dB in the operating band. The measured fractional 180° ± 10° bandwidth of the PLH TL balun is 71% from 1.47 GHz to 2.99 GHz. The maximum unbalance of two outputs is measured at 0.7 dB in the operating band. It is theoretically demonstrated that the wideband balun designed with the modified PLH TL has the fractional bandwidth of 107.8%.

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1.75-KILOWATT CONTINUOUS-WAVE OUTPUT FIBER LASER USING HOMEMADE YTTERBIUM-DOPED LARGE-CORE FIBER

Bing He,[1,2] Jun Zhou,[1,2] Qihong Lou,[1,2] Yuhao Xue,[1,2] Zhen Li,[1,2] Wei Wang,[1,2] Jingxing Dong,[1,2] Yunrong Wei,[1,2] and Weibiao Chen[1,2]

[1] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China; Corresponding author: bryanho@mail.siom.ac.cn

[2] Shanghai Key Laboratory of All solid-state Laser and Applied, Shanghai, 201800, China

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ABSTRACT: *We have demonstrated a homemade high-efficient ytterbium-doped fiber laser with up to 1.75 kW of continuous-wave output power at 1.09 μm with a slope efficiency of 76%. The fiber is pumped by two laser diode array (LDA) sources launched through opposite ends. No undesirable effect is observed with increasing pump power, which suggests that the homemade fiber laser could produce higher power output by using more pump sources.* © 2010 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 1668–1671, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25226

Key words: *fiber laser; laser diode array; large mode area*

1. INTRODUCTION

Because of proven advantages, such as compactness, efficiency, and beam quality, fiber lasers are becoming the geometry of