fore, if the tapered angle of PWG diminishes, then the tuning resolution of the SPF filter increases.

4. CONCLUSIONS

A tunable SPF filter with a tapered PWG, which effectively utilize the relation between the thickness of the PWG and the shift of the resonant wavelength, was used to make a tunable EDF ring laser. When the tapered PWG slide laterally, the thickness of PWG changed due to its tapered angle. As a result of experiments with an SPF filter with a tapered PWG, the resonant wavelength changed according to the lateral displacement of the tapered PWG, so that the tuning resolution was 0.046 nm per 10 μm of transversal slide of the PWG whose tapered angle was 0.000286°. Also, the tuning resolution doubled by replacing the 0.000286° tapered PWG angle with 0.000143°. Therefore, changing the tapered angle of PWG resulted in a different tuning resolution. The SPF filter using a tapered PWG angle of 0.000286° was then used in an EDF ring laser to tune the lasing wavelength. As a result of the tuning experiment, the EDF ring laser bilaterally tuned the lasing wavelength from 1549 to 1565 nm. Furthermore, no additional energy was needed after tuning the lasing wavelength. Therefore, the proposed filter can be effectively used in a tunable EDF ring laser. Plus, FSR of the proposed filter can be adjusted by changing the thickness of the PWG.

ACKNOWLEDGMENT

This work was supported by the Brain Korea 21 Project in 2006.

REFERENCES

1. K.-R. Sohn and J.-W. Song, Thermooptically tunable side-polished fiber comb filter and its application, IEEE Photon Technol Lett 14 (2002), 1575–1577.
2. K.-R. Sohn and K.T. Kim, Multiwavelength all-fiber ring laser using side-polished fiber comb filter and mechanically formed long-period fiber gratings, IEEE Photon Technol Lett 17 (2005), 309–311.
3. K.T. Kim, S. Hwangbo, G.I. Kweon, and S.R. Choi, Widely tunable filter based on side-polished polarisation maintaining fiber coupled with thermo-optic polymer overlay, Electron Lett 40 (2004), 1330–1332.
4. K.T. Kim, S. Hwangbo, J.P. Mah, and K.R. Sohn, Widely tunable filter based on coupling between a side-polished fiber and a tapered planar waveguide, IEEE Photon Technol Lett 17 (2005), 142–144.
5. H. L. An, X.Z. Lin, E.Y.B. Pun, and H.D. Liu, Multi-wavelength operation of an erbium-doped fiber ring laser using a dual-pass Mach-Zehnder comb filter, Opt Commun 169 (1999), 159–165.

DOUBLE-CLADDING Yb^{3+} FIBER FOR FREE-SPACE OPTICAL COMMUNICATION

Yong Kong[1] and Chunyu Wang[2]
[1] No. 23 Research Institute, China Electronics Technology Group Corporation, Shanghai 200437
[2] Shanghai Institute of Optics and Fine Mechanics, The Chinese Academia of Science, Shanghai 201800

Received 25 August 2006

ABSTRACT: *The experiment result of Nd:YVO$_4$ laser pumped by laser diode that was amplified by double-cladding Yb^{3+} fiber is reported. Stable mode-locking pulses are obtained at repetition rate of 320 MHz and the output power is 15 mW. When laser power is amplified by Yb^{3+}-doped double-cladding fiber amplifier, its power can get to 600 mW. Based on these, experiment of double-frequency is carried out, and green laser with power of 4 mW is obtained.* Microwave Opt Technol Lett 49: 889–892, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22264

Key words: *laser diode; Nd:YVO$_4$; repetition rate; plane-parallel cavity; Yb^{3+}-doped; double-cladding; fiber amplifier; double-frequency*

1. INTRODUCTION

In many application field, such as in the laser sensor, radar, optic communication, and so on, [1–3] especially in optical communication systems, lasers with high repetition rate and high peak power are required. At the same time, system must have small size, compact structure, longevity, and stable performance for long-term operation. Active mode-locked solid state laser amplified by Yb^{3+}-doped double-cladding fiber can satisfy these requirements. So it is important to study it in the laser application field.

Experimental investigation of the mode-locked solid state laser undergoes two stages. First stage is from early 60's to end of 70's last century, most of the pumping source are pumped by flashlamp. Representative experiments were studied by DiDomenico, Ostenrik, Foster, and Waddington. Especially, Waddington who studied Nd:YAG laser with acoustic-optic modulator obtains mode-locked laser at repetition rates of 164, 174, 180, 196, and 200 MHz respectively, and he analyzed the stable performance of the mode-locked laser. Second stage is from 80s to now. There are two characteristics. Firstly, pumping source is LD instead of traditional flashlamp; LD pumping can decrease thermal load and improve stable performance of the laser system, furthermore, pulse width obtained in experiment is more narrow than that estimated in the theory [4, 5]. Secondly, advanced acoustic-optic medium is applied to experiment. The modulator can be drived by higher power and thus it can break through high frequency diffraction limit of fused quartz. So the repetition rate of active mode-locked laser can be very high [6, 7].

High-power, compact, reliable, and efficient low-noise lasers have been the subject of significant experimental activity in recent years [8–11]. For example, several types of high-power, cladding-pumped, single-mode lasers operating in the wavelength region of 1030–1100 nm have recently been demonstrated. The erbium-doped fiber amplifier has attracted great interest, especially for its major commercial applications in the field of communication technology. However, EDFA cannot provide specific wavelength. Ytterbium-doped fibers can provide amplification over the very broad wavelength range from ~975 to ~1200 nm, and this is expected to generate increasing interest in the near future. Apart from their broad-gain bandwidth, Yb^{3+}-doped fiber amplifiers can offer high output power and excellent power conversion efficiency. Many of the complications that are well-known from erbium-doped amplifiers are avoided: excited state absorption and concentration quenching by interionic energy transfer do not occur, and high doping levels are possible, which lead to high gain in a short length of fiber. The broad bandwidth is ideal for the amplification of ultrashort pulses, and the high saturation fluence allows for high pulse energies.

In this study, we reported Nd:YVO$_4$ mode-locked laser amplified by double-cladding Yb^{3+} fiber. This system will play an important role in free-space optical communication.

2. EXPERIMENT SETUP

Schematic diagram of the mode-locked laser setup is shown in Figure 1. Laser light emitted from laser diode is coupled into fiber 7 through beam-shaping system 3. Light is focused by focusing

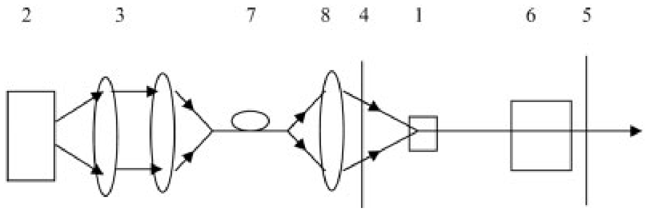

Figure 1 Schematic diagram of a diode end-pumped acousto-optical mode-locking $Nd:YVO_4$ laser. 1, $Nd:YVO_4$; 2, Laser diode (808 nm); 3, Optical lens; 4, Input cavity mirror; 5, Output cavity mirror; 6, AOM; 7, Transmitting optical fiber; 8, Focus lens

lens 8 on the laser medium 1. Laser is formed in the optical cavity, which consists of the mirrors 4 and 5. Acousto-optic modulator 6 that provides periodical attenuation causes output of mode-locking pulses. Laser medium is $Nd:YVO_4$ doped 1 wt%, whose size is 4 mm × 4 mm × 4 mm. $Nd:YVO_4$ is appropriate for being pumped by laser diode, because it has a big excited emission area and a board absorption band near 809 nm. Furthermore, $Nd:YVO_4$ is a kind of high-quality birefringent crystal. Output laser is linearly polarized along the special π direction, which can avoid thermal birefringence and decrease the loss of the cavity [12].

Medium of acousto-optic modulator consists of fused quartz whose length along the direction of optical propagation is 10 mm and both sides of the medium are coated antireflection coating at 1064 nm. $LiNbO_3$ acts as a transducer whose drive frequency is 160 MHz. When the drive power is 4.5 W, its diffraction efficiency for the He-Ne laser is $\eta = 30\%$.

According to the formula in Ref. 12,

$$\eta = \sin^2\left(1.4\frac{0.6328}{\lambda} L\sqrt{M_\omega I_S}\right). \quad (1)$$

When the wavelength is 1064 nm, diffraction efficiency is ~11%, whereas it is only 7% in actual measurement. According to equation in Ref. 4,

$$\eta = \frac{1}{2}\left[1 - J_0(2\theta_m)\right]. \quad (2)$$

The percentage modulation θ_m is 0.36. Plane-parallel cavity is applied in the experiment, because it has the virtue of easy operation at fundamental traverse-mode and higher beam quality of the output light. Beam quality parameter M^2 measured in the experiment is 1.5. Divergence angle almost reaches its limit. This is very important in the free-space optical communication.

Schematic diagram of amplification of Yb^{3+}-doped double-cladding fiber setup is shown in Figure 2, pump wavelength is 940 nm, signal wavelength is mode-locking light. The Yb^{3+}-ion concentration is 6500 ppm; the diameters of the active core and the D-shaped pump core are 10.6 μm (NA = 0.16) and 400 μm (NA = 0.38), respectively. Compensating plate is used to guarantee the pump and the signal transmit in the same optical axis, and the achromatic and aspheric focusing technology is used.

3. RESULTS OF EXPERIMENT

Firstly, the experiment is operated with drive frequency $f_s = 81$ MHz. The stable mode-locking condition is that modulation frequency is exactly equal to $c/2L$, where c is velocity of light and L is length of the cavity. According to the equation, the valid length of the cavity is $L = 926$ mm. Considering the influence of modulator and laser crystal, actual length of the cavity is 916 mm.

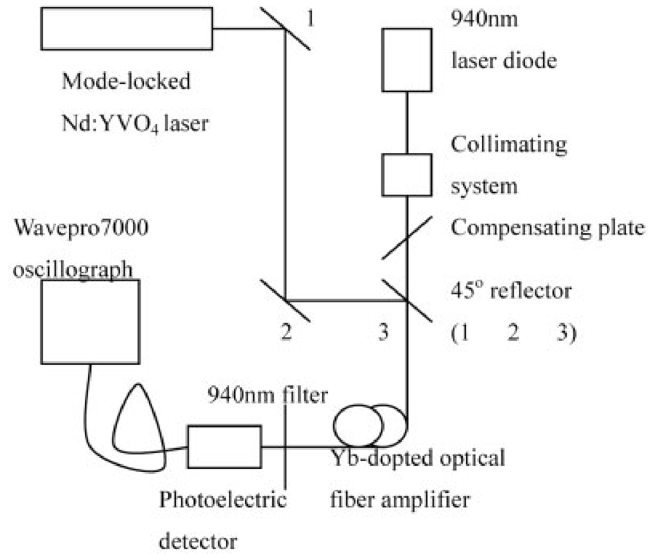

Figure 2 Schematic diagram of amplifier and detecting system

An output mirror with transmittance of 3.6% is placed at the point where actual length of the cavity is 916 mm. Threshold value of the pumping current I_{th} of the hollow cavity is 15.2 A and power of laser diode is shown in Figure 3.

When the acousto-optic modulator is put into the cavity, the threshold value of the pumping current I_{th} increases to 15.8 A. At same time, we turn on drive power, and adjust acousto-optic modulator so that the Bragg condition is satisfied. When the diffraction is maximum, the threshold current I_{th} is 16.9 A. Cavity length is adjusted precisely, meanwhile, the output waveform is monitored by PIN photo diode and TDS3052B mode sampling oscillograph. When the pumping current is 17.5 A, mode-locking effect is found. Waveform on the oscillograph is shown in Figure 4. Response time of the PIN photodiode is 1ns, and sampling rate and bandwidth of the oscillograph are 1GS/s and 500M respectively. Since monitor system limits, the pulse width is not given here.

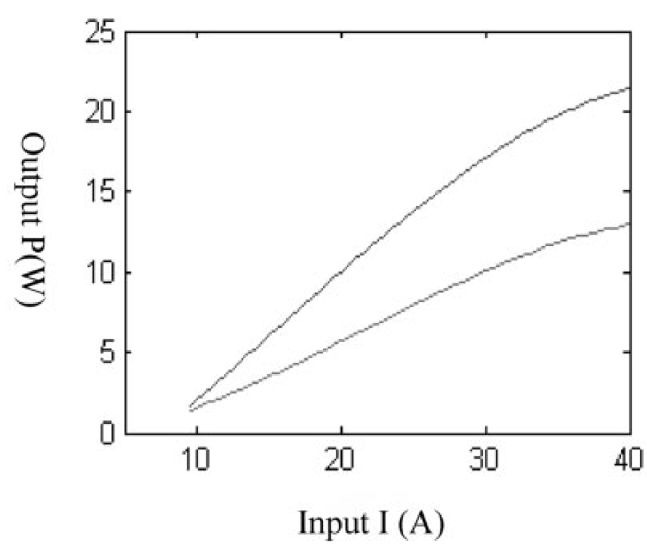

Figure 3 Plot of the output power of laser diode at 808 nm versus input circuit

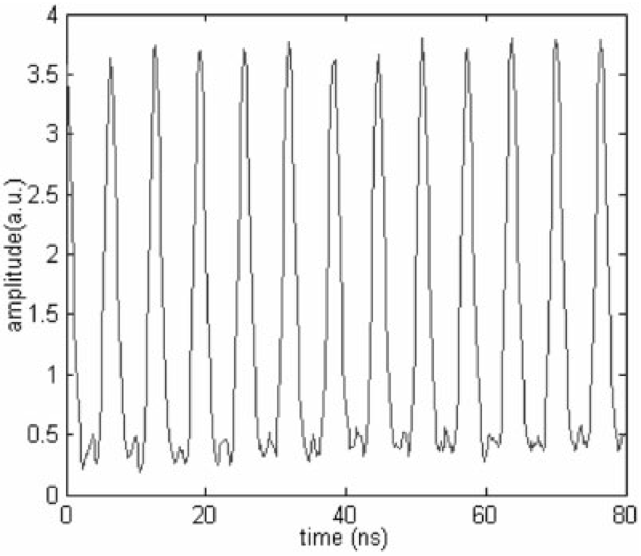

Figure 4 Output waveform of mode-locked Nd:YVO_4 laser at 320 MHz repetition rate

It is difficult to find precisely the cavity length using the PIN photodiode and TDS3052B mode sampling oscillograph as the monitor. To lock mode at higher frequency, we use higher response time photodetector (response time is 200 ps) and Wavepro7000 mode oscillograph (whose bandwidth is 1 GHz, and sampling rate is 10 GS/s) as the monitor. The photodetector's sensitivity is low; the laser output power is weaker. Laser output power under continuous wave operation is only over 10 mW. To monitor output waveform, the small light signal is put into Yb^{3+}-doped double-cladding fiber amplifier. Then, the amplified signal is put into the photodector to monitor. The monitor system is shown in Figure 2.

Experiment is operated at f_m = 159.98 MHz, valid cavity length is 452 mm, driving power is 5 W, reflectance of the modulator is less than 0.5 W, and Bragg diffraction efficiency is about 7%. When I = 15.8 A, stable mode-locking pulse train is obtained, repetition rate of pulse is 319.9 MHz. Figure 5 shows the self-oscillating spectrum of 5-m fiber end face that is not disposed,

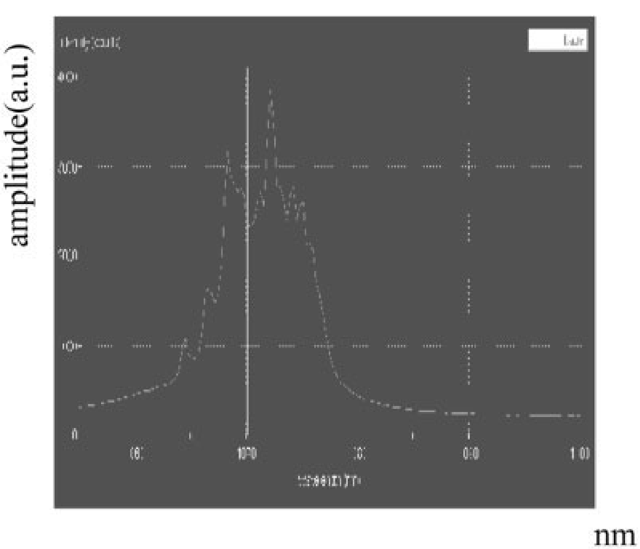

Figure 5 The self-oscillating spectrum of 5-m fiber that is not disposed

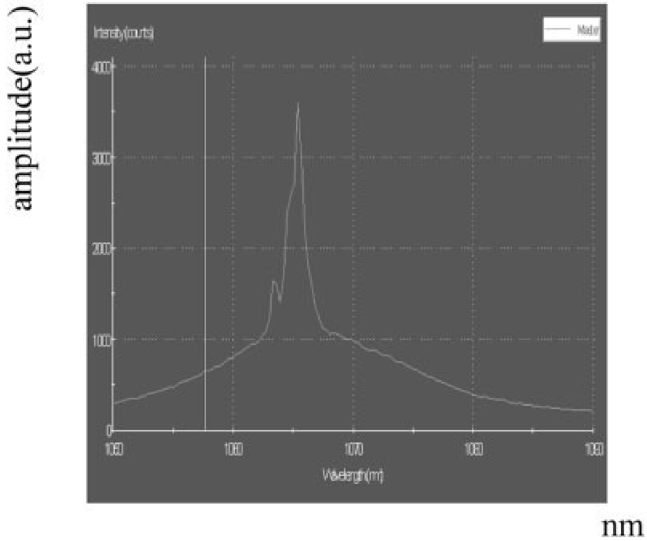

Figure 6 The self-oscillating spectrum of 5-m fiber that is disposed

and Figure 6 shows the self-oscillating spectrum of 5-m fiber end face that is milled for 10°. No signal amplification was found in experiment when the fiber end face was not disposed, and when the fiber end face is milled for 10°, the amplified signal gain is as shown in Figures 7–9. Figure 7 shows the signal gain versus 808-nm power current when 940-nm power current is invariable, and Figure 8 shows the signal gain versus 940-nm power current when 808 nm power current is invariable. The result agrees with the theory analysis [10]. The signal amplification waveform recorded by Wavepro7000 oscillograph is shown in Figure 9. The pulse width is almost not changed after being amplificated. At this time, output power of the laser is 15 mW before the amplifier power, and power is 600 mW after being amplified. When the double-frequency crystal KDP is inserted into the cavity, green light with continuous power of 4 mW is obtained.

4. DISCUSSION OF THE RESULTS

When the repetition rate is 320 MHz, average width of mode-locking pulse recorded by Wavepro7000-mode oscillograph is about 600 ps, minimum of the average width is 400 ps. Bandwidth

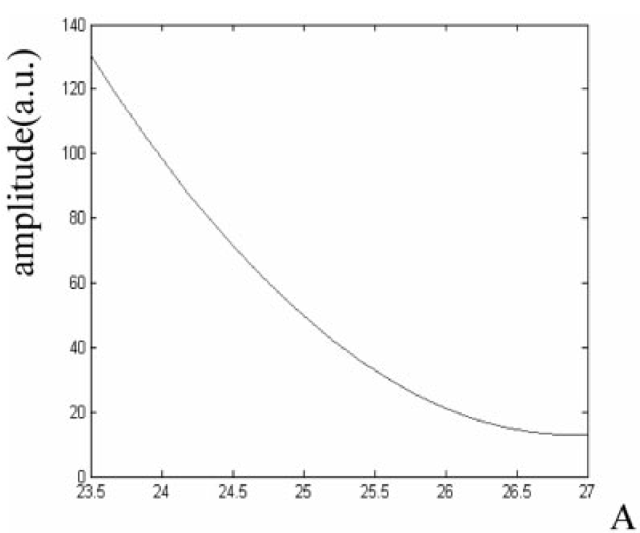

Figure 7 Signal gain versus 808-nm power current

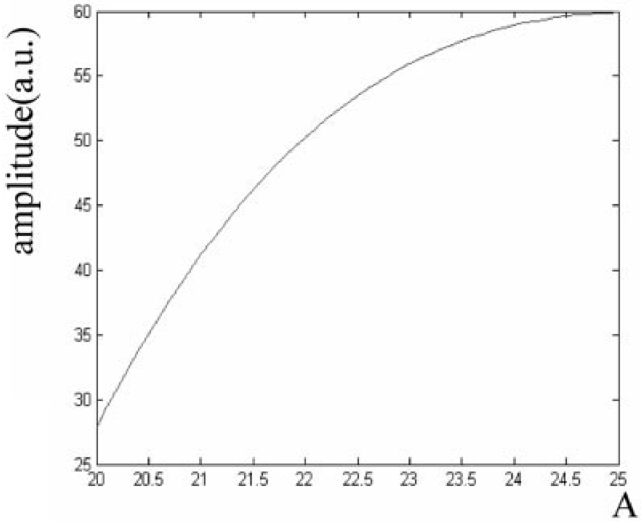

Figure 8 Signal gain versus 940-nm power current

of the oscillograph is 1 GHz, so it can only be used to measure pulse width of 1 ns without distortion. The oscillograph's measurement limit is several hundreds of picoseconds, so the actual pulse width ought to be more narrow. Without locking mode, double frequency is so weak that power meter with order of milliWatt almost has not any response, but with locking mode, the output power of green light is strengthened significantly, which indicates that the peak power is increased significantly. In addition, width of spectral lines of the Nd:YVO_4 near 1064 nm is observed by spectra-meter with locking mode and without locking mode, respectively. Comparing with experiment results, spectral line is almost not broadened significantly when mode is locked. Because every optical elements are parallel, serious etalon effect makes the number of the longitudinal mode that can be locked to decrease. If one wants to obtain very narrow pulse, this effect must be suppressed. Aim of our research is to provide high power laser and excellent beam quality at high repetition rate for optical communication system, much more sharp pulse is not the purpose that we are going for. In the system of amplification of Yb^{3+}-doped double-cladding fiber, when pump input power is invariable, signal

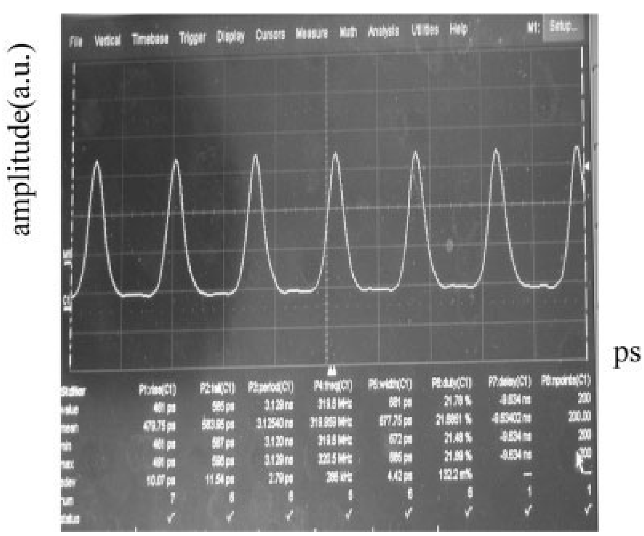

Figure 9 Output waveform of mode-locked Nd:YVO_4 laser at 320 MHz repetition rate

input power is increased, the signal gain will saturate gradually, and when signal input power is invariable, pump input power is increased, the signal gain will also saturate gradually. If high signal gain is wanted to be get, high pump power and longer fiber will be required.

5. CONCLUSION

We have reported an acousto-optic mode-locking experiment of Nd:YVO4 laser pumped by laser diode and amplified by Yb^{3+}-doped double-cladding fiber amplifier. Using plane-parallel cavity, we obtain stable mode-locking pulse train with repetition rate of 320 MHz and the average power is 15 mW. After it is amplified by optical fiber amplifier, continuous power is 600 mW. At last, double-frequency is carried out, and green laser with power of 4 mW is obtained.

REFERENCES

1. H. Plaessmsnn, K.G. Yamada, et al., Sub-nanosecond pulse generation from diode-pumped acoustic-optical Q-switched solid-state lasers, Appl Opt 32 (1993), 6616.
2. R. Scheps, J.F. Myers, and G. Mizell, High-efficiency 1.06-μm output in a monolithic Nd:YVO4 laser, Appl Opt 33 (1994), 5546–5549.
3. Y. Kitaoka, S. Ohmori, K. Yamamoto, et al., Stable and efficient green light generation by intracavity frequency doubling of Nd:YVO4 laser, Appl Phys Lett 63 (1993), 299–301.
4. H. Li and W. Hu, Chin J Lasers 17 (1997).
5. Y. Chen and F. Zhou, Chin J Lasers A22 (1995).
6. K.J. Weingarten, D.C. Shannon, R.W. Wallace, and U. Keller, Opt Lett 15 (1990).
7. G.T. Maker and A.I. Ferguson, Appl Phys Lett 54 (1989), 403.
8. R. Paschotta, J. Nilsson, and A.C. Tropper, Ytterbium-doped fiber amplifiers, IEEE J Quantum Electron 33 (1997), 1049–1056.
9. D.C. Hanna, R.M. Percival, and I.R. Perry, Continuous wave oscillation of a monomode ytterbium-doped fiber laser, Electron Lett, 24 (1988), 1111–1113.
10. J. Nilsson and R. Paschotta, Yb^{3+}-ring-doped fiber for high-energy pulse amplification, Opt Lett, 22 (1997), 1092–1094.
11. J.Y. Allain, M. Monerie, H. Poignant, et al., High-efficiency ytterbium-doped fluoride fiber laser, J Non-Cryst Solids 161 (1993), 270–273.
12. X. Lan, The laser technology, Science Publisher, 2000, pp. 51–113.

RECEIVING MUTUAL IMPEDANCE BETWEEN TWO PRINTED DIPOLE ANTENNAS

W. M. Lee,[1] Y. Yap,[2] and H. T. Hui[2]
[1] A*STAR (I2R)-RadioSystem, Teletech Park, Singapore 117674
[2] School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, QLD 4072, Australia

Received 25 August 2006

ABSTRACT: *A new mutual impedance, the receiving mutual impedance, between two printed dipole antennas was rigorously determined by experimental measurements. The variations of the receiving mutual impedance with antenna separation and with frequency were obtained. The receiving mutual impedance obtained differs significantly from the conventional mutual impedance, which was shown to be not suitable to indicate the mutual coupling effect in receiving arrays. Results are useful for printed dipole array design.* © 2007 Wiley Periodicals, Inc.