Transmission-Line Model for Analyzing the Coupling between Two Parallel Micro/nano-fibers

Zehua Hong, Xinwan Li*, Jianguo Shen, Xiaowei Shen, Xiaocao Yu, Minwen Zhou, Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks,
Shanghai Jiao Tong University,
Shanghai 200030, P. R. China
Corresponding author: lixinwan@sjtu.edu.cn

Abstract—**The coupling behavior between two parallel micro/nano-fibers is investigated by extending the theory of transmission-lines (TL) to optical domain, Simulation result indicates that the energy transfer length of micro/nano-fibers based coupler is much shorter than that of conventional fiber based coupler. The experiment of the coupling behavior of micro/nano-fibers is demonstrated. It verifies the TL model of micro/nano-fiber coupler. This result may offer valuable reference for the investigation of nano-photonic devices.**

Keywords-transmmision-lines model; micro/nano-fiber coupler; nano-photonic devices

I. Introduction

Because of low loss, easy fabrication and small size, micro/nano-fibers have been studied widely [1-6] and micro/nano-fiber based compact photonic devices such as couplers [7], Mach-Zehnder interferometers [8], all-fiber filters [9], all-fiber Fabry-Perots [10], lasers [11] attract development interests. In these photonic devices, coupler consisting of two parallel micro/nano-fibers is the basic unit. So investigation of its performance is of great significance. In conventional methods, the coupler is considered as a weakly coupled system and perturbation theory is usually applied. However, in the case of nano-sale, it can no longer be treated as a weakly coupled system. In order to get the mode coupling between micro/nano-fibers, one may solve Maxwell's equations. Of course it is a difficult work.

TL model is of significant importance for the design and analysis of microwave networks. Recently, Nader Engheta proposed to analyses photonic nanoelement by transferring the electrical engineering TL theory into the optical regime [12]. Such a concept provides a new way for investigating nano-scale photonic devices in the optical domain. In this paper, a transmission-line (TL) model for the coupling between two parallel micro/nano-fibers is presented. It is aimed to give a novel method to deal with strongly coupled system.

II. TL Model for Micro/Nano-Fiber Based Coupler

It turns out that nano-particle can be treated as lump circuit element. The material can determine the type of lumped impedance. For example, if the nano-particle is made of material which the real part of electric permittivity ε is larger than 0 (Re (ε) > 0) at optical domain, the nano-particle can be treated as a capacitive impedance; if the particle is composed of material with Re (ε) <0 at optical wavelength, the nano-particle will act as an inductive impedance; and if loss exist, a resistor should be considered [13]. Following this concept, the TL model for micro/nano-fiber based coupler is set up.

The micro/nano-fiber based coupler is shown in Fig. 1. The coupling length is about 0.9 mm and the diameter of two parallel micro/nano-fibers is about 800 nm, respectively. Between two micro/nano-fibers, there is a thin layer of air. From the concept of Nader Engheta [12], the micro/nano-fiber can be treated as many nanostructures that get together closely. In the limit, the micro/nano-fiber may be envisioned to constitute layered transmission lines.

Fig. 2 is the TL model for micro/nano-fiber coupler. As is known, the material of optical fiber is SiO_2 and Re (ε) is larger than 0, so the nanoscale optical fiber act as nano-capacitor; the loss of optical fiber almost always exist, hence the nano-resistor should be included in the TL model. Lastly, the thin air between two fibers also behaves as capacitive impedance because of its Re (ε) >0. According the circuit theory, the TL model for micro/nano-fiber should be a parallel-series circuit. The air-nano capacitors play the role of coupling, transferring the energy from one optical fiber to another. The value of capacitance is similar to the coupling coefficient, which determines the speed of energy transfer.

For simplification, we make the following assumption:

(1) The thin air has a cylindrical shape as shown in Fig. 3.
(2) Every nano-capacitor composing micro/nano-fiber has the same impedance, the same to the air.
(3) Every resistance of nano-resistor is identical.

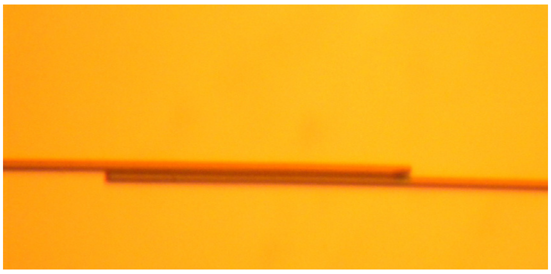

Figure 1. Micro/nano-fiber based coupler

This work was supported in part by National Science Foundation of China (NSFC) (ID90704002, 60877012), STCSM Project (09JC1408100) and Hangtian Research Institute- SJTU Joint Foundation. State Key Lab Project (GKZD030004).

978-1-4244-7595-7/10/$26.00 ©2010 IEEE

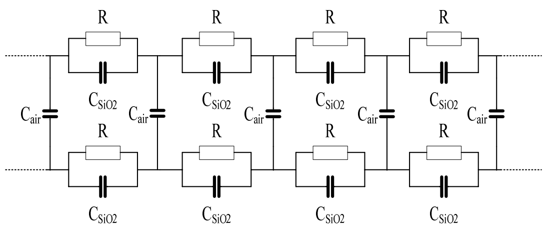

Figure 2. The transmission-lines model for micro/nano-fiber coupler

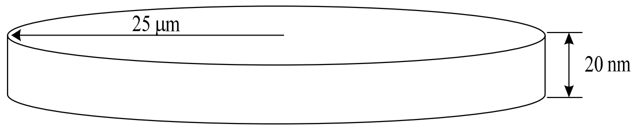

Figure 3. The model for thin air between two fiber

III. SIMULATION RESULT AND DISCUSSION

Using the TL model set up in section II, the coupling behavior between two micro/nano-fibers is simulated. In simulation, the impedance of nano-capacitor is simply given by [14]:

$$Z = (-j\omega\varepsilon d / l)^{-1} \quad (1)$$

So, we can get

$$C = \varepsilon \frac{d}{l} \quad (2)$$

where, C is capacitance of nano-capacitor, l is the length of nano-capacitor, d is the cross-sectional size, ω is the angular frequency of optical, j is the imaginary unit, and ε is the real part of electric permittivity.

To get the parameter values of these nanostructures, let us assume the nano-capacitor of micro/nano-fiber with radius 400 nm and length 50 µm. The parameter of air nano-capacitor is shown in Fig. 3. The permittivity of SiO_2 and air is known to be $\varepsilon_{SiO2} = 3.58\varepsilon_0$. From Eq. (2), we can then find $C_{SiO2} = 0.319 attoF$. If the nanostructure is made of air with permittivity $\varepsilon_{air} = 1.00\varepsilon_0$, the capacitance of air nano-capacitor will be $C_{air} = 0.870 pF$. Here, we do not take the wavelength dependence of permittivity into account and we set the value of resistor at $R = 0.115 m\Omega$ according the loss of micro/nano-fiber coupler.

From these parameters, using circuit theory, the simulation result can be obtained. Fig. 4 shows the theoretical coupling behavior of two micro/nano-fibers. In this figure, the energy transfer from one micro/nano-fiber to another is similar to weakly coupled system. However, the minimum transfer length (L_{min}) for energy exchange is much shorter than that in weakly coupled waveguides because of the stronger coupling coefficient between two micro/nano-fibers. From the figure, L_{min} for maximum value of energy exchange is about 0.4 mm. In weakly coupled system, L_{min} is usually more than ten millimeters.

The experiment results for a micro/nano-fiber coupler as shown in Fig. 1 is also presented in Fig. 4. It can be seen that they have the similar behavior and the experimental value of L_{min} is about 0.45 mm. There is discrepancy between two results, which may arise from the difference in parameter choice.

The above results suggest that two close micro/nano-fibers exhibit strongly coupling, which is essential for developing compact photonic devices. It will reduce the size of integrated optical interconnect device.

.

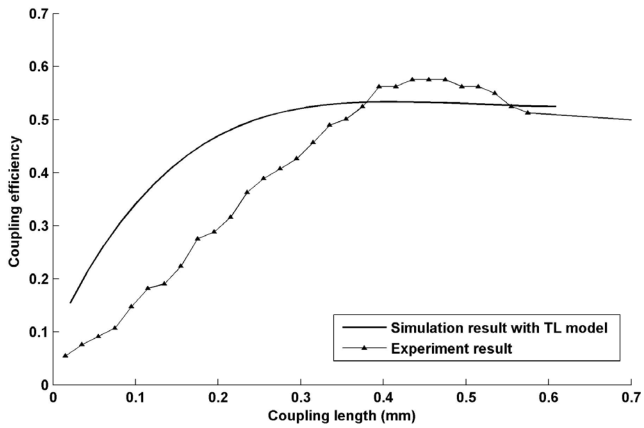

Figure 4. The relationship between the coupling efficient and the coupling length

IV. CONCLUSION

We presented and discussed a simple method for investigating the coupling between two micro/nano-fibers by extending the TL theory from microwave to optical domain using the concept proposed by Nader Engheta. Simulation and experimental results are given. Comparison of the simulation result with experimental one verifies that the TL model is valid. It provides a simple way for the analysis of nanostructure based nano-photonics devices.

References

[1] Limin Tong, Rafael R. Gattass1, and Jonathan B. Ashcom1, “Subwavelength-diameter silica wires for low-loss optical wave guiding,” NATURE, VOL 426, pp. 816-819, December 2003.

[2] Limin Tong, jingyi Lou, and Eric Mazur, “Single-mode guiding properties of subwavelength-diameter silica and silicon wire waveguides,” OPTICS EXPRESS, VOL 12, pp. 1025-1035, March 2004.

[3] Gilberto Brambilla,Vittoria Finazzi, and David J. Richardson, “Ultra-low-loss optical fiber nanotapers,” OPTICS EXPRESS, VOL 12, pp. 2258-2263, May 2004.

[4] Masaya Nogi, Shinichiro Iwamoto, and Antonio Norio, “Optically Transparent Nanofiber Paper,” Adv. Mater, VOL 21, pp. 1595-1598, 2009.

[5] Xiang-Fa Wu, and Yuris A. Dzenis, “Size effect in polymer nanofibers under tension,” JOURNAL OF APPLIED PHYSICS, VOL 102, 044306, 2007.

[6] T. T. Tan and H. S. Sim, “X-ray generation using carbon-nanofiber-based flexible field emitters,” APPLIED PHYSICS LETTERS, VOL 88, 103105, 2006.

[7] L. M. Tong, J. Y. Lou, and R. R. Gattass, "Assembly of silica nanowires on silica aerogels for microphotonic devices," Nano. Lett. VOL 5, pp. 259–262, 2005.

[8] Yuhang Li and Limin Tong, "Mach–Zehnder interferometers assembled with optical microfibers or nanofibers," OPTICS LETTERS, VOL 33, pp. 303-305, February 2008.

[9] Xiaoshun Jiang, Yuan Chen, and Guillaume Vienne, "All-fiber add–drop filters based on microfiber knot resonators," OPTICS LETTERS, VOL 32, pp. 1710-1712, June 2007.

[10] Shan-Shan Wang, Zhi-Fang Hu, and Yu-Hang Li, "All-fiber Fabry–Perot resonators based on microfiber Sagnac loop mirrors," OPTICS LETTERS, VOL 34, pp. 253-255, February 2009.

[11] Xiaoshun Jiang, Qinghai Song, and Lei Xu, "Microfiber knot dye laser based on the evanescent-wave-coupled gain," APPLIED PHYSICS LETTERS, VOL 90, 233501, 2007.

[12] Nader Engheta, Alessandro Salandrino, and Andrea Alu`, "Circuit Elements at Optical Frequencies: Nanoinductors, Nanocapacitors, and Nanoresistors," PRL, VOL 95, 095504, 2005.

[13] Nader Engheta, "Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials," SCIENCE, VOL 317, pp.1698-1702, September 2007.

[14] Andrea Alu, and Nader Engheta, "All Optical Metamaterial Circuit Board at the Nanoscale," PRL, VOL 103, 143902, 2009.