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Study of Millimeter Wave Phase Shift in 40 GHz Hybrid Mode Locked Lasers

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***Abstract*—An investigation into using hybrid mode-locked lasers to implement millimeter wave phase shift is presented. The phase shift is measured directly using a vector network analyzer enabling straightforward characterization of such systems. Both magnitude and phase of the modulation response are measured and a "plateau" is observed in the magnitude response which corresponds to the locking range of the system. Phase shifts of greater than 90° are observed and such devices could have application in millimeter wave radio-over-fiber phased array antenna systems.**

***Index Terms*—Millimeter wave (mm-wave), mode locked laser (MLL) , vector network analyzer.**

I. INTRODUCTION

MODE-LOCKED lasers (MLLs) are widely used in a number of applications including optical clock recovery, optical time division multiplexing and packet switching [1], [2]. Typically they are fabricated from a standard Fabry–Perot (FP) laser which has a short saturable absorber (SA) section placed within the cavity. When the SA section is reversed biased, longitudinal modes within the cavity become synchronized resulting in pulsed emission of light with a repetition frequency determined by the cavity round trip time. For typical device lengths around 1 mm this results in millimeter wave (mm-wave) repetition frequencies and thus in combination with high speed photodiodes can be used as millimeter wave sources. It is well known that by inputting an RF signal into the SA section injection locking can occur where the "free running" frequency of the mode locked laser (MLL) becomes controlled by the injection signal. This is the hybrid mode-locking regime which results in very stable, low phase noise signals which are important in a number of optical communications applications.

A number of workers [3]–[5] have shown that this approach can be used to directly modulate lasers well beyond their conventional bandwidths and that baseband data can be transmitted using such techniques. This makes these devices ideal, low cost sources for mm-wave radio-over-fiber systems which traditionally rely on expensive external modulators in the mm-wave bands. In [4] it was shown that the phase locking that occurs enables mm-wave phase shifting to be implemented. This occurs due the fact that under injection locked conditions the mm-wave frequency of the MLL is controlled by the external locking signal. Thus, if an attempt is made to change the MLL frequency by changing the SA bias for example, the MLL frequency cannot change and thus the only option available for the system is a change in phase. This has important applications in Radio-Over-Fiber (RoF) systems, in particular in phased array antennas [4] where long fiber links can be used to send mm-wave signals to arrays of many thousands of antennas. Typically each antenna element would require its own electronic phase shifter and associated control circuitry; This MLL based technique enables this to be preformed completely remotely from the antenna, reducing the requirement at the array to a photodiode and amplifier in each element. In this letter a novel technique to characterize the phase-locking phenomenon is presented which uses the phase locked nature of a vector network analyzer (VNA). Fig. 1 shows the configuration where port 1 of the VNA is used to input a signal into the SA section to produce hybrid mode locking. Light is coupled out of the laser and into a high speed photodiode and back into port 2 of the VNA.

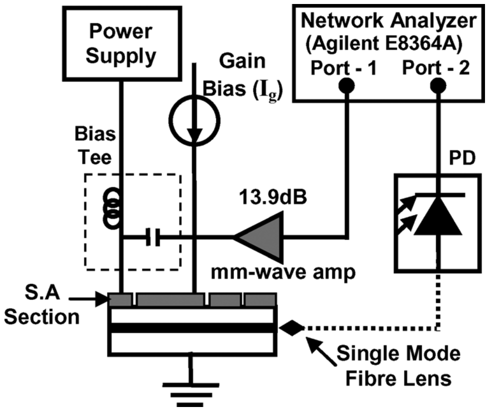

Fig. 1. MLL-A2 measurement setup using mm-wave amplifier for phase shift measurements.

Measurement of S_{21} then characterizes the modulation response of the system in terms of both magnitude and phase. Across the locking range of the MLL a strongly enhanced modulation response is observed which is well beyond the conventional direct modulation bandwidth. The locking range is observed as a flat "plateau" in the S_{21} amplitude response where the swept frequency of the VNA is locking the free running frequency of the MLL. Parameters of the MLL can then be changed and the induced phase shift can be observed directly.

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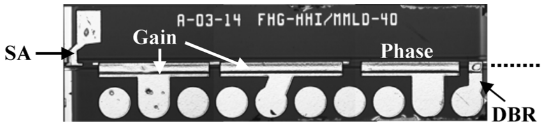

Fig. 2. MLL device used in the measurements.

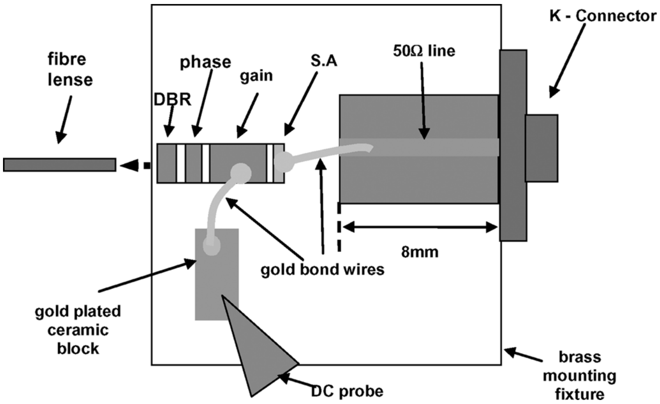

Fig. 3. Schematic of mounting configuration for MLL testing.

These phase shifting techniques have applications in low cost smart antenna systems for mm-wave wireless LANs where antenna arrays could scan an office environment with multiple beams to deliver very high speed wireless internet. These will most likely be at 60 GHz [6] and this frequency can be achieved by reducing the MLL device length.

II. RESULTS

The MLLs being used have been supplied from HHI, Berlin [2]. They are multi-section devices comprising SA, gain and phase sections along with a Distributed Bragg Reflector (DBR) as shown in Fig. 2.

Two MLLs of the same design were characterized for these measurements and will be referred to as MLL-A1 and MLL-A2. Fig. 3 shows the device mounting configuration. The MLLs were mounted on brass fixtures and the gain section was connected using a bond wire to a separate gold plated ceramic block which was then probed to apply the forward bias to the gain section. A K-connector, 50 Ω transmission line and gold wire bond are used to apply both RF power and reverse bias to the SA section for hybrid mode-locking; this utilizes the built-in bias tees within the VNA. Care must be taken with the design of microstrip line, length of bond wire and transition from K-connector in order to ensure good performance at 40 GHz. Both MLL-A1 and MLL-A2 have excellent output power characteristics giving more than 5 mW and 3.5 mW of optical power into a fiber lens respectively at $15^{\circ}\mathrm{C}$ and 50 mA gain section current. Initially passive mode locking results are presented. Using MLL-A1, the gain section is forward biased with 110 mA and the SA voltage, $\mathrm{V_{sa}} = -1.0\ \mathrm{V}$.

The mm-wave spectrum is observed using a high speed $\mathrm{U^2T}$ Photonics 50 GHz photodetector and an Agilent 50 GHz spectrum analyzer. The result is shown in Fig. 4 and a well defined mode locking spectrum is observed. The free running frequency of the MLL can be controlled by the SA voltage and has a range of 400 MHz for a range of SA voltages and gain section bias currents as shown in Fig. 5. The free running frequency tuning range is an important parameter in these types of systems. It is well known from injection locking of electronic oscillators that this will control the amount of available phase shift [7]–[9].

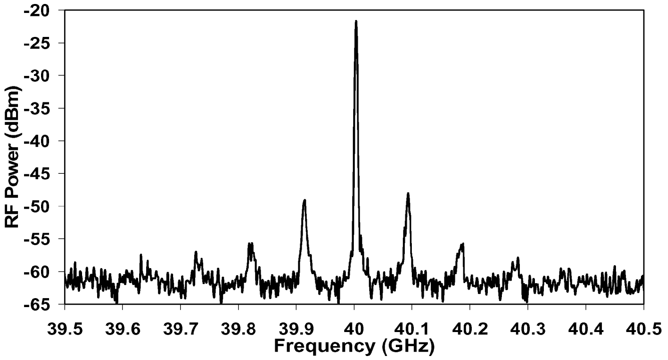

Fig. 4. Measured Millimeterwave spectrum of passive mode locking at $\mathrm{V_{sa}} = -1.0\ \mathrm{V}$ for MLL-A1.

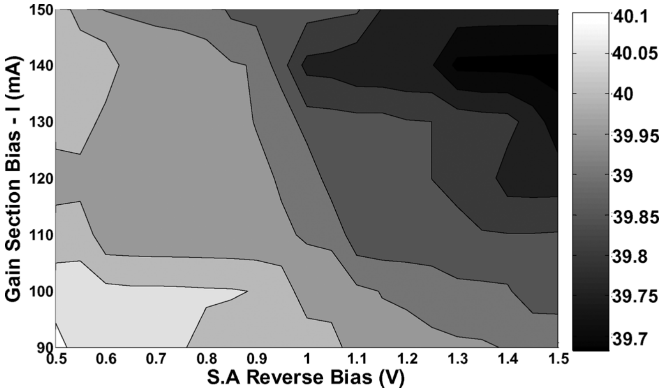

Fig. 5. Shows the tuning range for passive mode locking over a range of gain section and SA section bias values.

It should be remembered however, that the hybrid mode locking regime described here will be much more complex than the Van Der Pol-like oscillators studied in [7], [8].

Hybrid mode locking is then performed by RF injection locking of MLL-A2 as shown in Fig. 1. The gain section was biased at 110 mA and the SA section was biased at range of voltages from $-0.5\ \mathrm{V}$ to $-1.5\ \mathrm{V}$. The phase and DBR sections were unbiased for these measurements. The timing jitter in such configurations is mainly determined by the jitter of the injection signal and has been measured in [2] to be in the range 50–280 fs. To measure the modulation response, port 1 of the VNA is connected to a Hittite (HMC-ALH369) mm-wave GaAs low noise amplifier ($+13.9\ \mathrm{dB}$ gain) and then to the SA section. The output of the MLL is then fed through the single mode photodetector and back into port 2 of VNA. Fig. 6 below shows the amplitude of the modulation response. The low frequency modulation response can be seen to roll off around 5–10 GHz, however, strong resonant enhancement is observed around 40 GHz across the locking range of the MLL. The amount of injected power is another important parameter with greater input power producing increased locking ranges. The maximum VNA output power is $-6\ \mathrm{dBm}$ which after the amplifier, bias-T and V-K connectors results in 2.6 dBm input

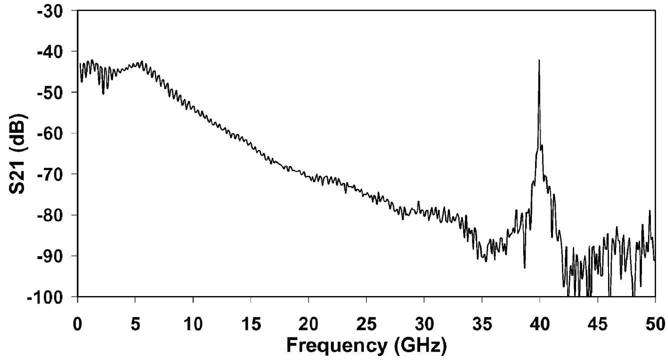

Fig. 6. Modulation Response of MLL-A2 under hybrid injection locking with gain section current of 110 mA and $V_{sa} = -1.1$ V.

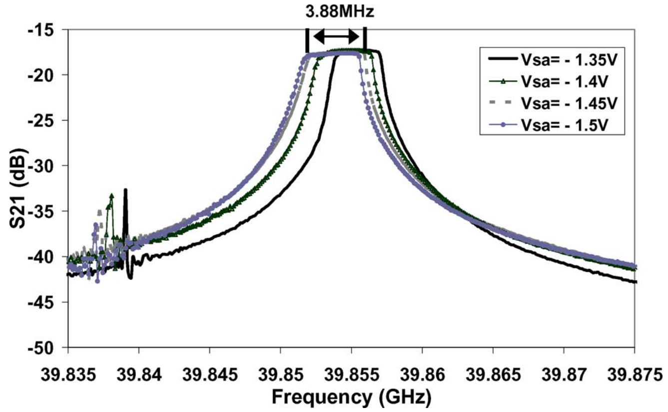

Fig. 7. Zoom-in on amplitude of modulation response showing plateau across locking range for different SA reverse bias values.

to the laser fixture. The loss from connector to SA section is estimated from separate fixture measurements to be 2 dB, thus the input power to the SA section is estimated to be $+0.6$ dBm. This is somewhat less RF injected power than is typically used for these devices which was > 10 dBm in [2] and accounts for the quite narrow locking ranges observed here. However, this power level is sufficient to observe locking ranges and phase shift performance.

Fig. 7 shows a zoom-in on the "plateau" region described above. It can be seen that the locking range can be tuned by changing the SA bias and the widest locking range occurs at $V_{sa} = -1.45$ V and is 3.88 MHz.

The phase measuring capability of VNA can now be used to observe the phase response and this is shown in Fig. 8. The results have been normalized to the phase at $V_{sa} = -1.35$ V. It can be seen that a phase shift of over 90° can be obtained over a narrow range of frequencies and across the range of V_{sa} values the amplitude response is remaining relatively flat resulting in good phase shifter performance. It is expected that much wider locking ranges and hence bigger phase shifts will be observed with higher injected powers. An important point to note here is the phase shift occurs only within the locking range between 39.85–39.86 GHz in Fig. 8 and outside the phase is relatively unchanged.

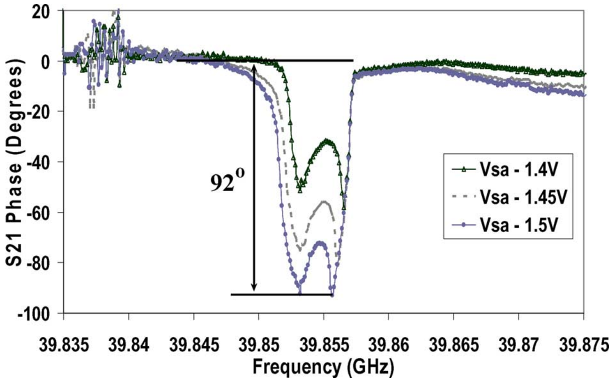

Fig. 8. Shows the injection locked Phase response at SA reverse bias of 1.4 V to 1.5 V, normalized to $V_{sa} = -1.35$.

III. CONCLUSION

This letter has shown how a VNA can be used to directly measure the induced phase shift in a hybrid mode locked laser system, enabling straightforward characterization of such systems. Such devices could have application in low cost wireless LAN smart antenna systems, especially at 60 GHz where radio-over-fiber is looking like a promising technology. This letter has explored tuning of the SA voltage, these devices can also be tuned with the gain, phase and DBR sections which should result in a number of novel configurations.

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