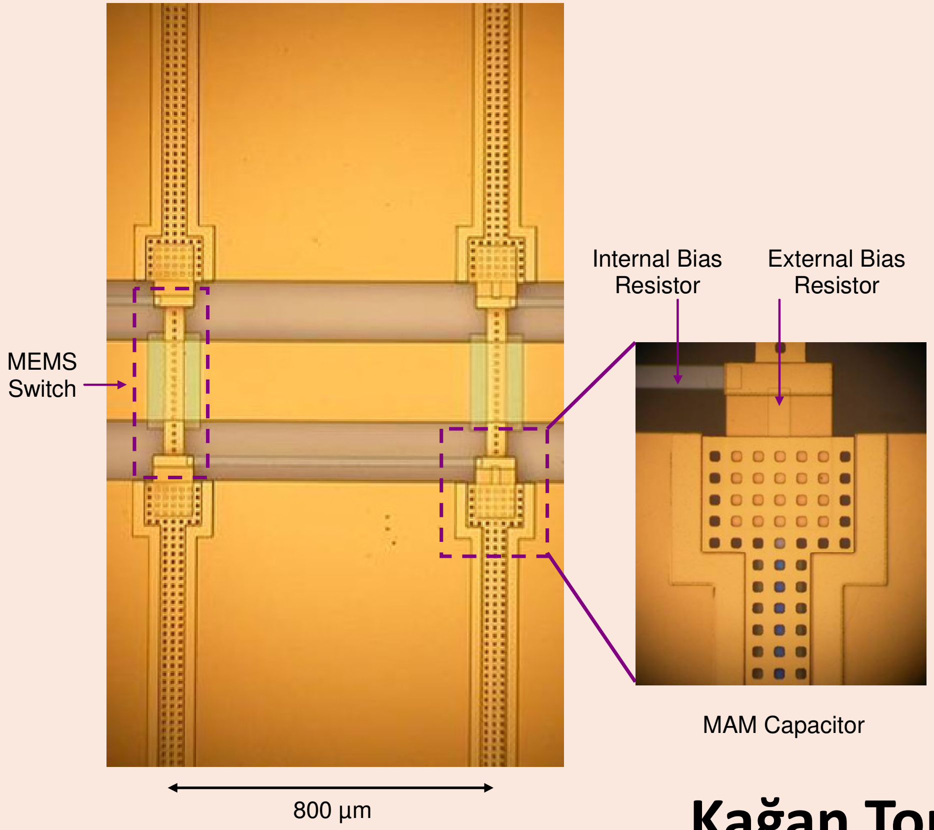
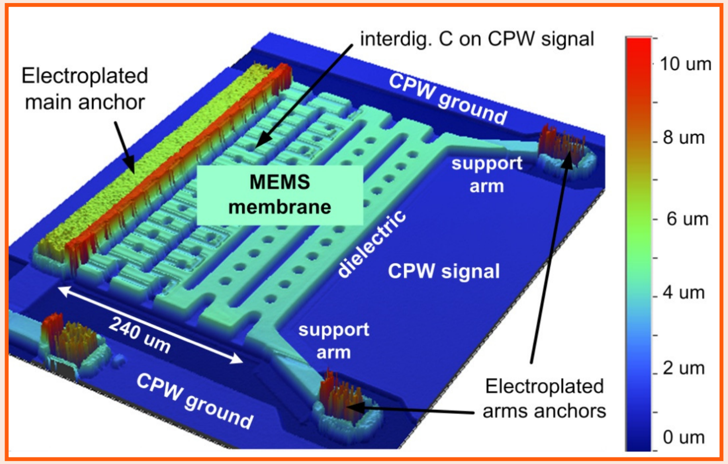
MEMS-based tunable true-time delay and composite right/left handed transmission lines

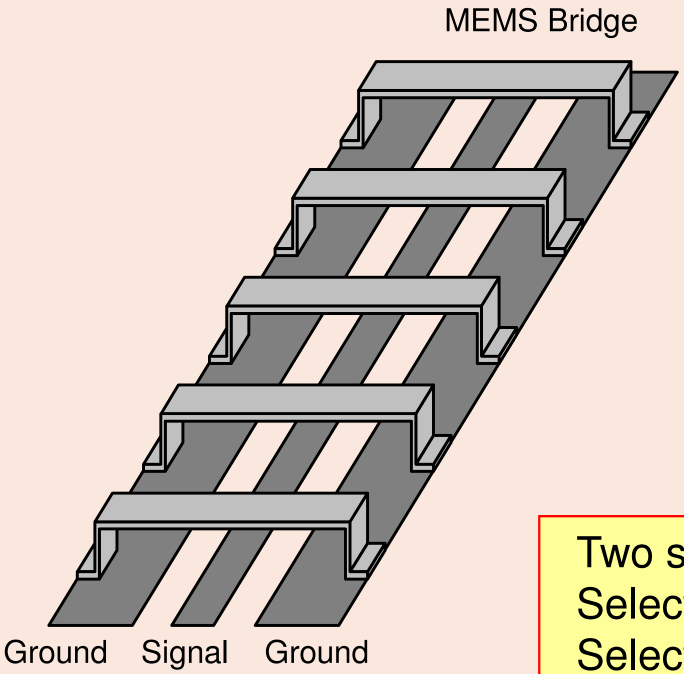


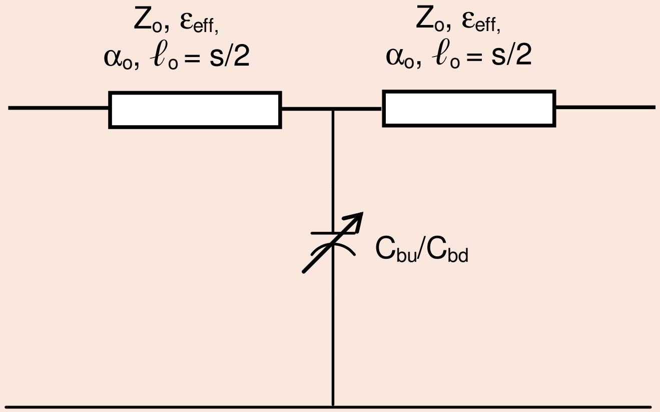


Kağan Topallı

National Nanotechnology Research Center
Institute of Materials Science and Nanotechnology
Bilkent University, Ankara, Turkey

Periodically loaded transmission lines





Two states for the loaded line impedances: Z_{lu} and Z_{ld}
Select Z_{lu} and Z_{ld} to have a return loss better than RL_{max}
Select the Bragg frequency, i.e., the cutoff freqeuncy: $f_B > 2f_o$

$$\Delta\phi = 360 s f_o \frac{Z_o\sqrt{\varepsilon_{eff}}}{c}\left(\frac{1}{Z_{lu}} - \frac{1}{Z_{ld}}\right)$$

RL_{max}	Z_{lu} (Ω)	Z_{ld} (Ω)
-20 dB	55.3	45.2
-15 dB	59.8	41.8
-10 dB	69.4	36.0

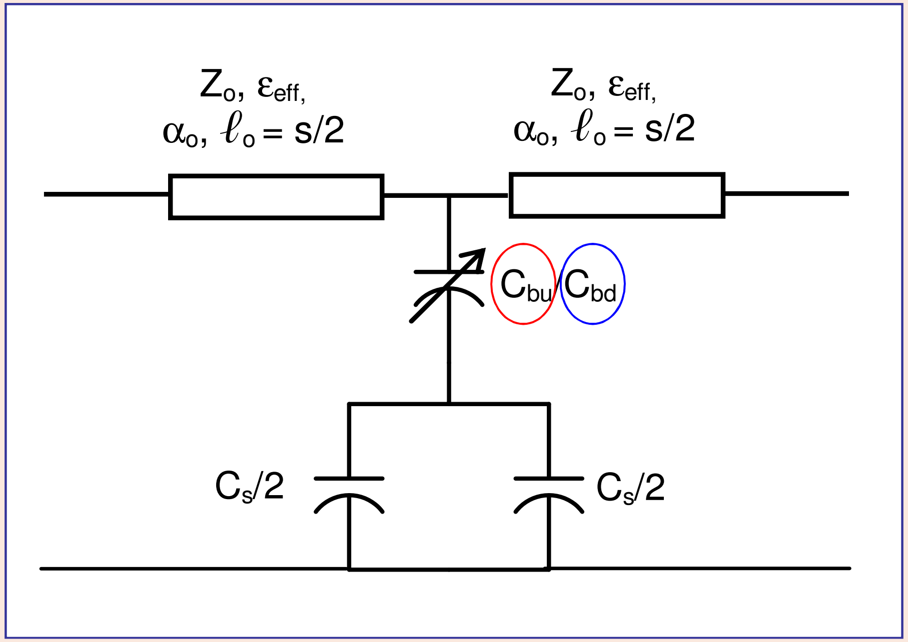
Distributed RF MEMS phase shifters

Increase C_r ~2.5 by employing static capacitors in series with MEMS switches

Digital design

RL_{max} ~- 15 dB (still acceptable)

Increased degree/dB performance



upstate

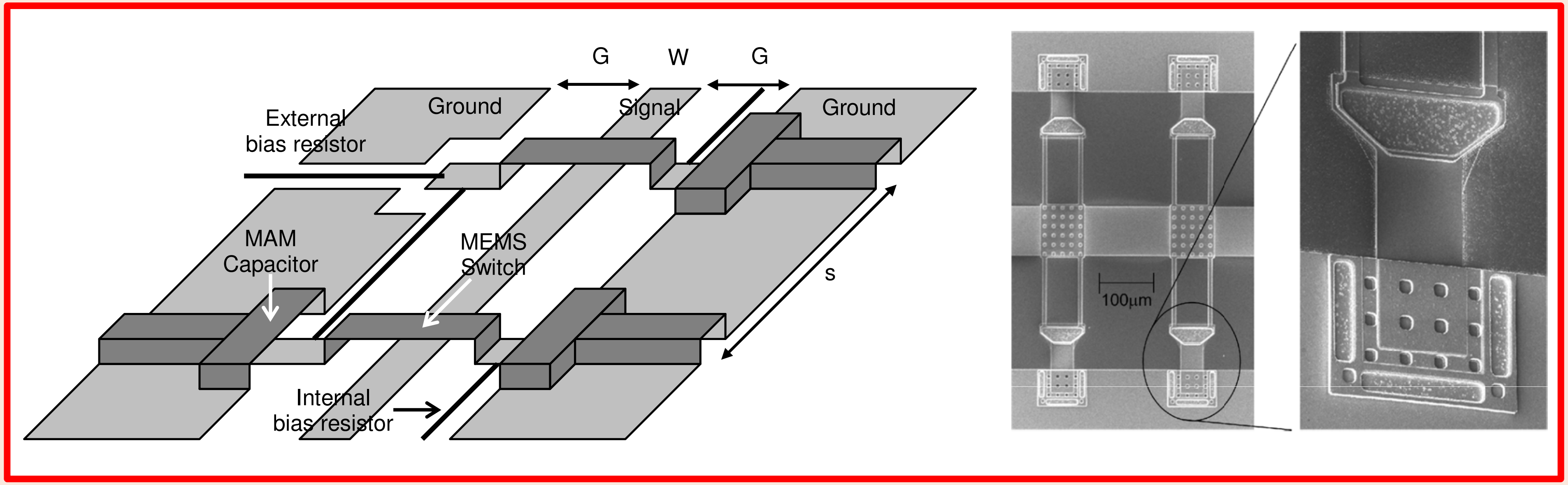
$$C_L = \frac{C_{bu} C_s}{C_{bu} + C_s}$$

downstate

$$C_L = C_s$$

$$C_r = \frac{C_{bu} + C_s}{C_{bu}}$$

Digital RF MEMS phase shifter

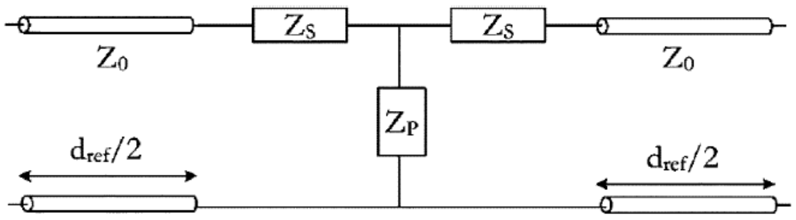


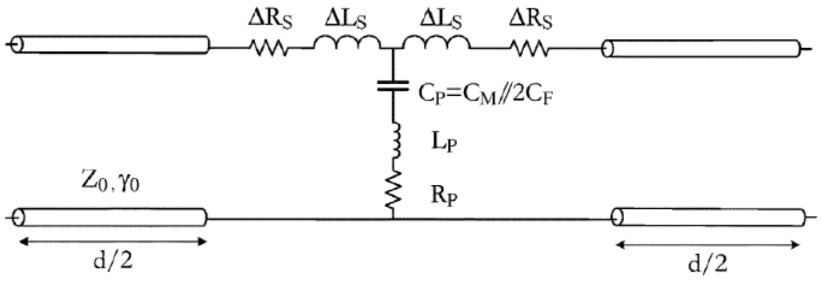
- High-Q MAM capacitor for static capacitor realization
- External bias resistors for each bit (only for three cells)
- Internal bias resistors to carry DC bias in each bit

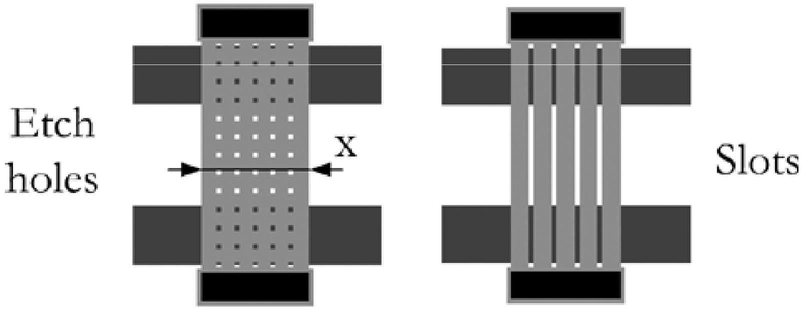
J. Perruisseau-Carrier, R. Fritschi, P. Crespo-Valero, A. K. Skrivervik, "Modeling of periodic distributed MEMS-application to the design of variable true-time delay lines," *IEEE Transactions on Microwave Theory and Techniques*, vol.54, no.1, pp.383,392, Jan. 2006

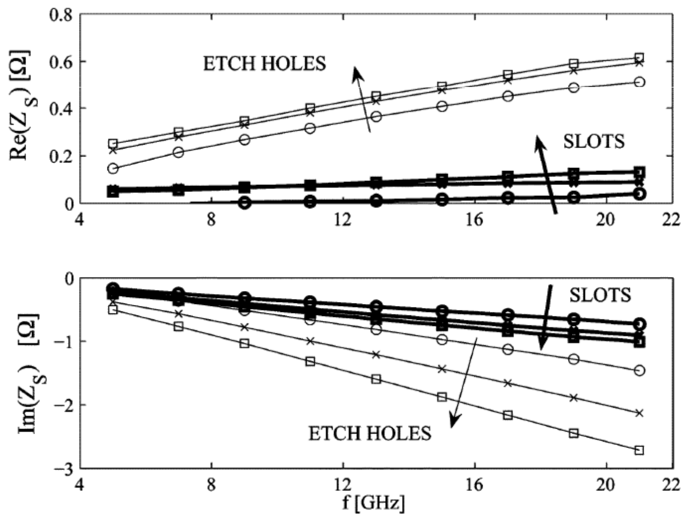
Modeling of true-time delay structures using distributed MEMS transmission lines

It is not enough for Julien to model the MEMS with a simple shunt capacitor









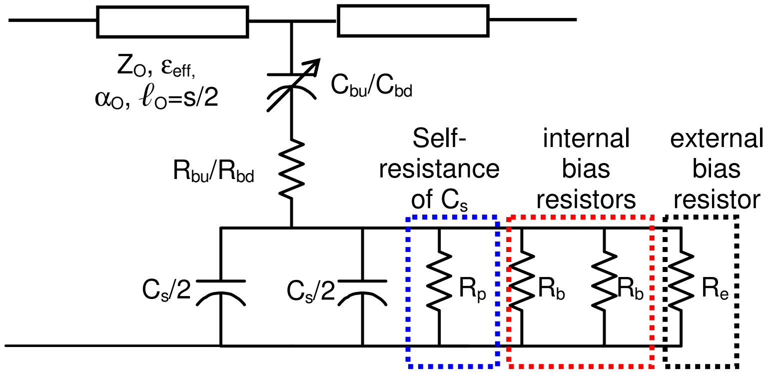
J. Perruisseau-Carrier, R. Fritschi, P. Crespo-Valero, A. K. Skrivervik, "Modeling of periodic distributed MEMS-application to the design of variable true-time delay lines," *IEEE Transactions on Microwave Theory and Techniques*, vol.54, no.1, pp.383,392, Jan. 2006

Inspired us to develop a similar model for such structures:

K. Topalli, M. Unlu, S. Demir, O. Aydin Civi, S. Koc, and T. Akin, “New Approach for Modeling Distributed MEMS Transmission Lines,” *IEE Proc.-Microw. Antennas Propag.*, vol. 153, no. 2, pp. 152-162, April 2006.

Digital RF MEMS phase shifter

Improved circuit model



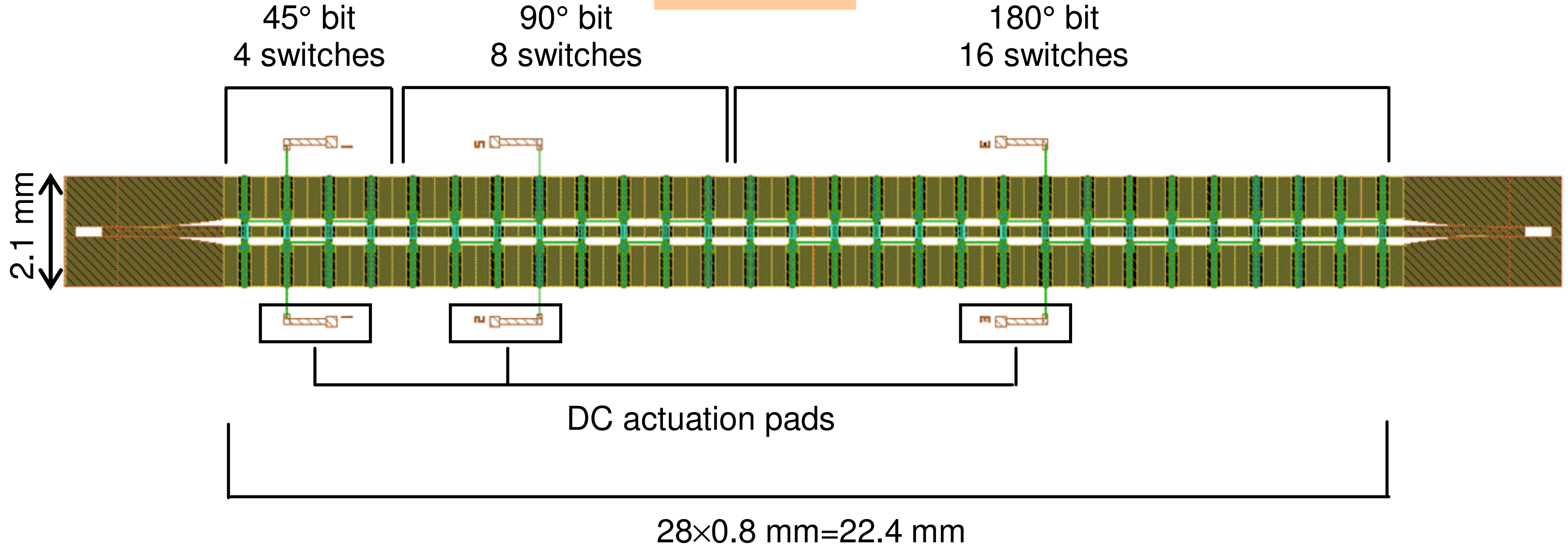
Distributed MEMS transmission line (DMTL) structure

Loaded (overall impedance), Z_L is switched from 58 Ω to 44 Ω

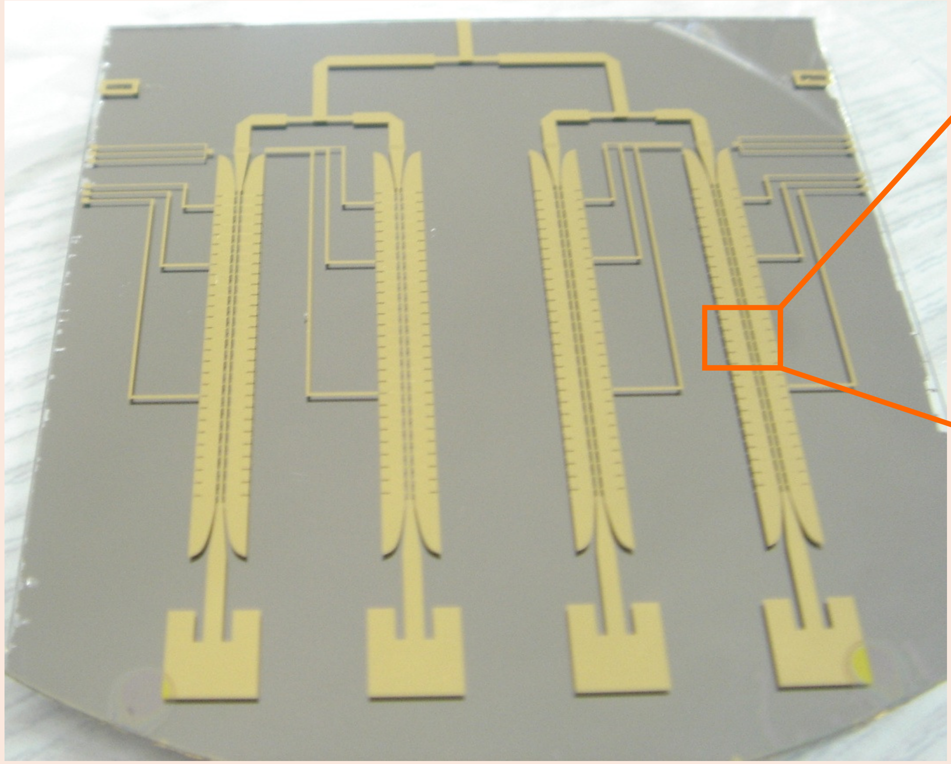
Unit cell provides ~11º

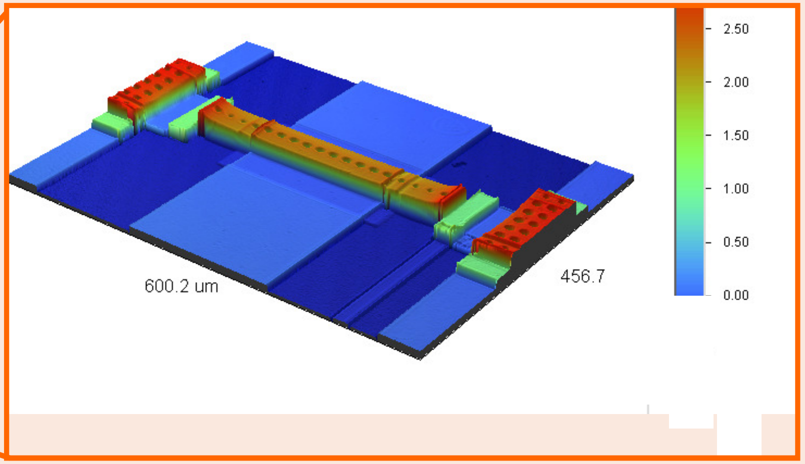
28 cells cascaded for a 3-bit structure

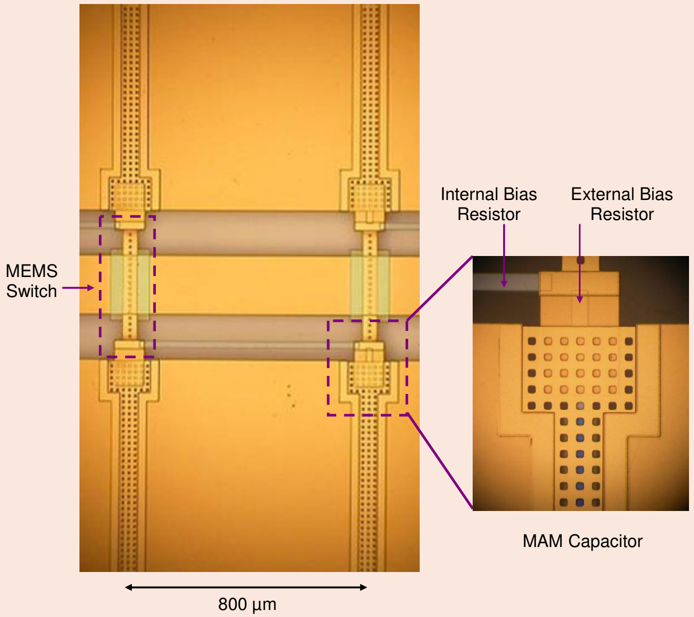
Layout



Monolithic Phased Array



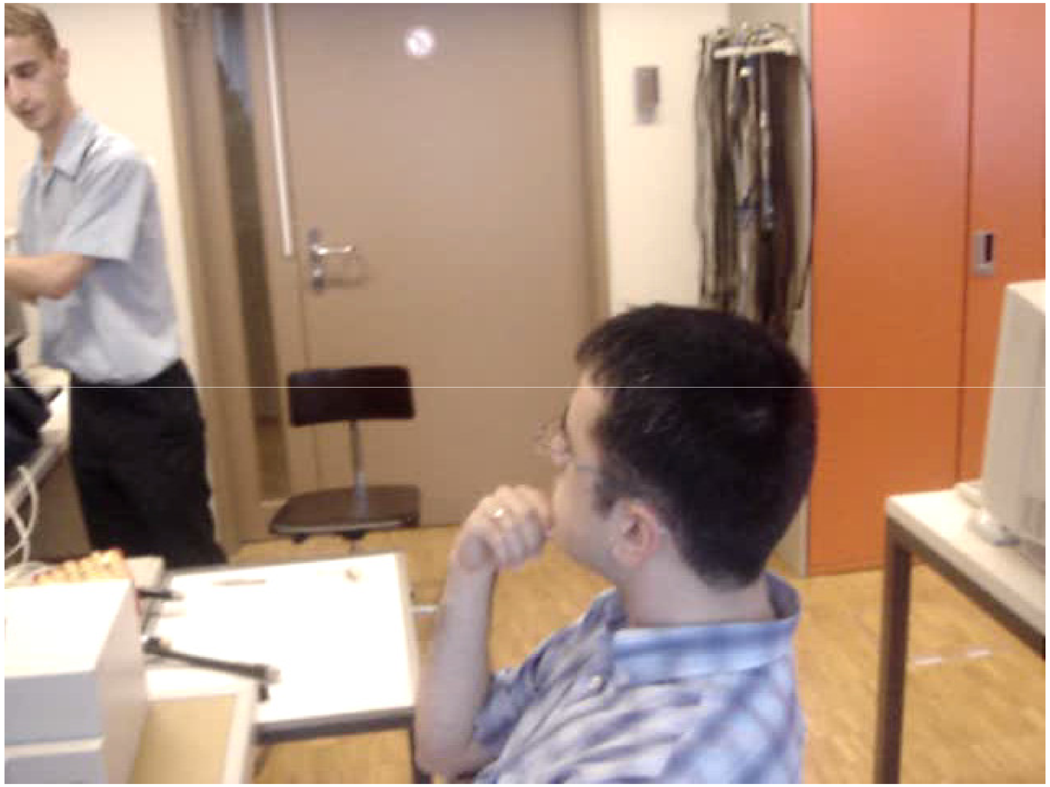




- One of the few examples in the literature
- Total area: 6 cm × 5 cm

K. Topalli, O. Aydin Civi, S. Demir, S. Koc, and T. Akin, "A monolithic phased array using 3-bit DMTL RF MEMS phase shifters," *IEEE Trans. Microwave Theory and Tech.*, vol.56, pp. 270-277, February 2008.

June 2005: Measurement sessions at EPFL-LEMA



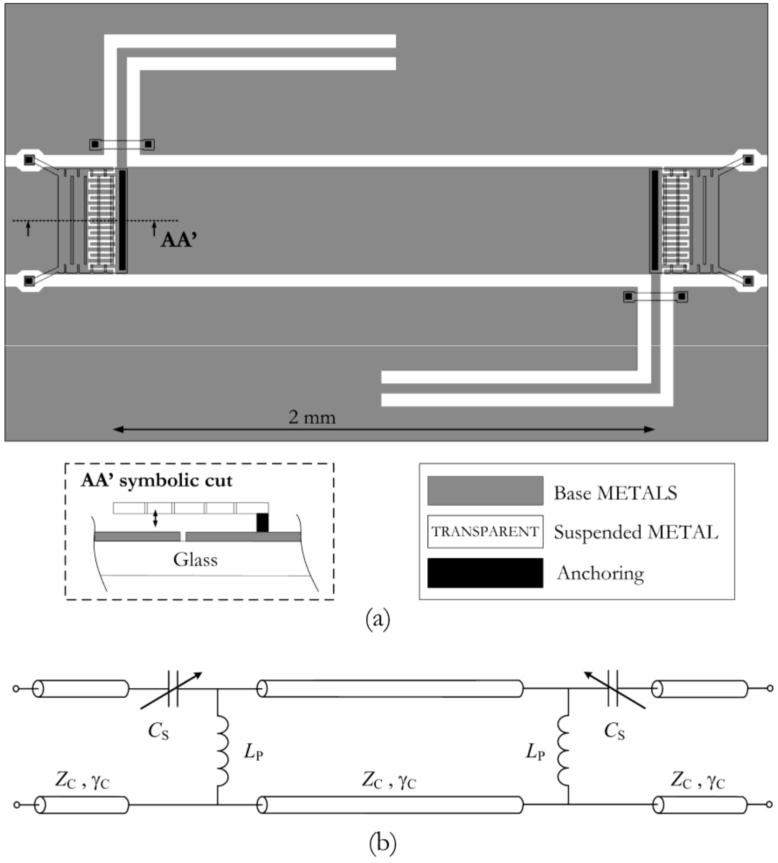
Interested in learning Turkish

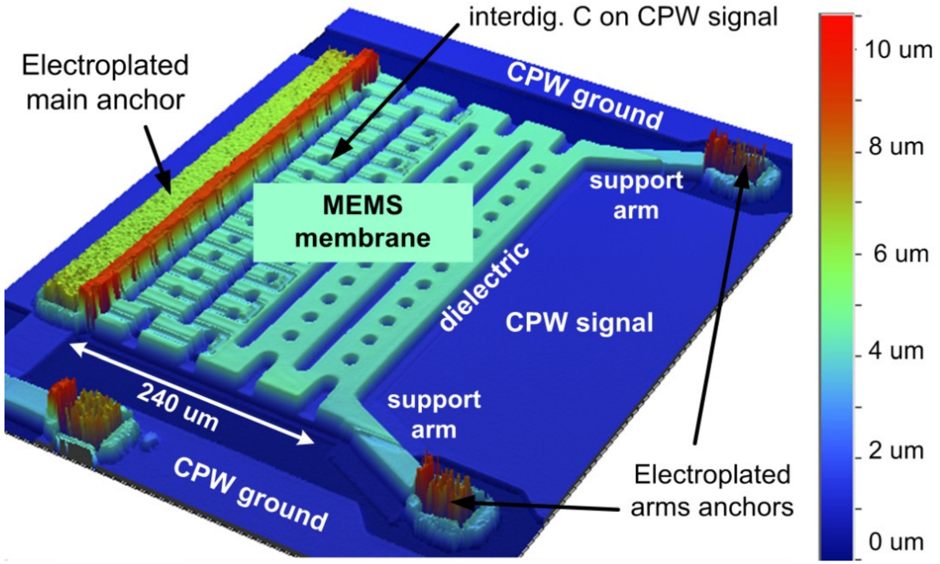
31.10.2005; Julien wrote:

Nasilsiniz ? Cok isiz var mi?
Yarin Istanbul'a gitiyorum, ama bu defa ankara'ya gitmecegim...
Ok, that is enough for now
......

See you soon,
Julien

Julien’s contribution to CRLH Transmission Lines

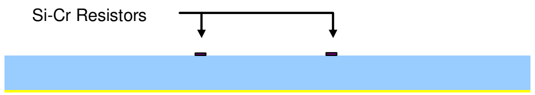




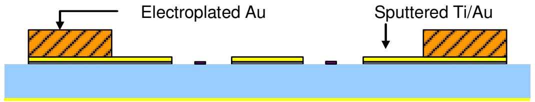
J. Perruisseau-Carrier, A.K. Skrivervik, "Composite right/left-handed transmission line metamaterial phase shifters (MPS) in MMIC technology," *IEEE Transactions on Microwave Theory and Techniques,* vol.54, no.4, pp.1582,1589, June 2006.

J. Perruisseau-Carrier, K. Topalli, and T. Akin, “Low-loss Ku-band Artificial Transmission Line with MEMS Tuning Capability,” *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 6, pp. 377-379, June 2009.

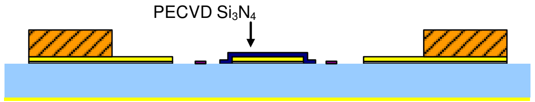
CRLH Transmission Line



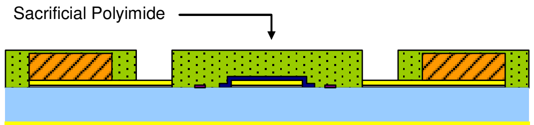
(i) Sputter Si-Cr on a glass wafer and pattern



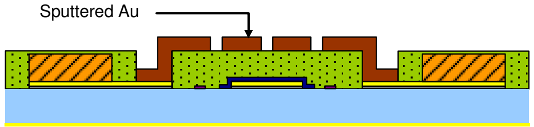
(ii) Sputter Ti/Au, electroplate Au, and patttern Ti/Au



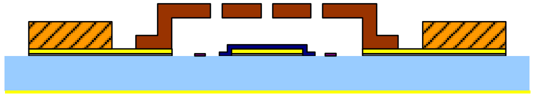
(iii) Deposit PECVD Si_3N_4 and pattern with RIE



(iv) Spin polyimide and pattern for anchors

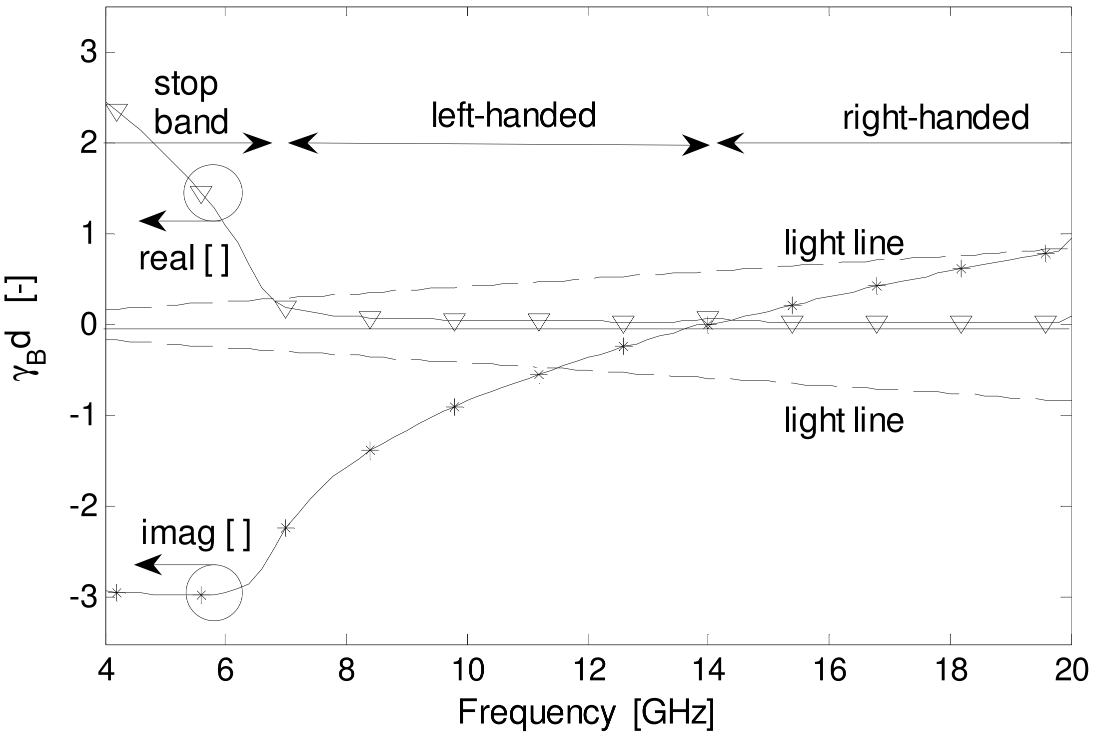


(v) Sputter Au structural layer and pattern the bridges



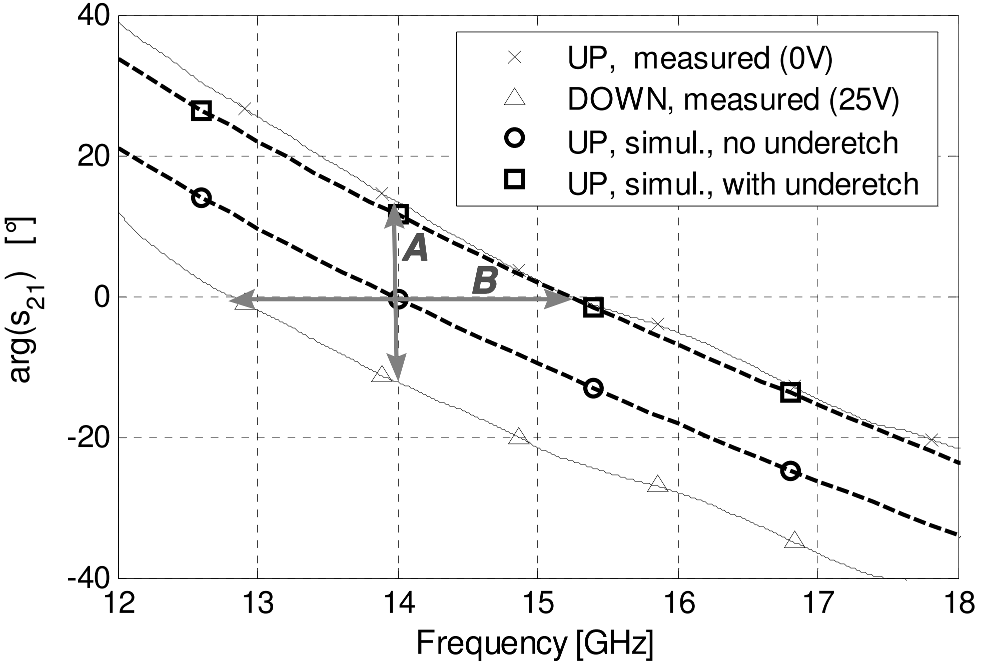
(vi) Etch sacrificial polyimide and release

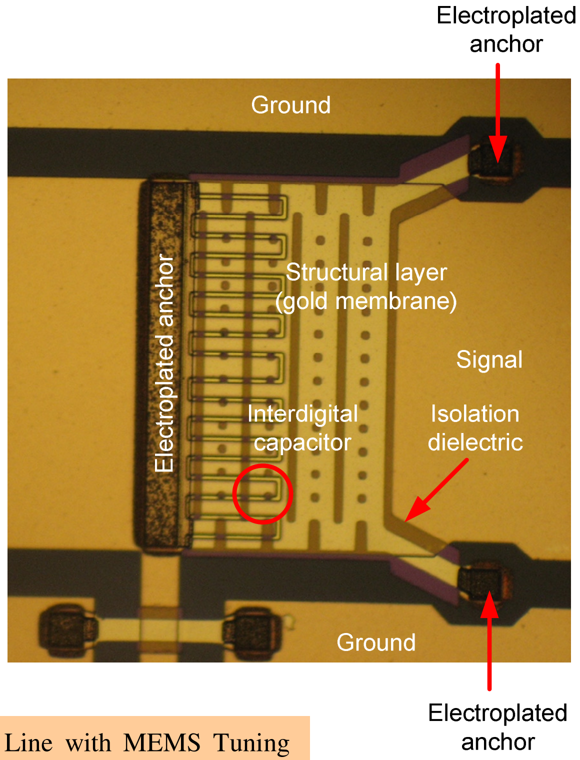
Simulation results



- MEMS process on glass substrate
- Reconfigurable leaky-wave antennas and series feed networks.
- Differential phase shift over losses (38°/dB at 14 GHz)
- Quasi-zero drive power consumption
- Monolithic and has a total footprint of $4mm^2$.

CRLH Transmission Line





J. Perruisseau-Carrier, K. Topalli, and T. Akin, “Low-loss Ku-band Artificial Transmission Line with MEMS Tuning Capability,” *IEEE Microwave and Wireless Components Letters*, vol. 19, no. 6, pp. 377-379, June 2009.

- A CRLH cell to exhibit a controllable negative/zero/positive phase shift at a given frequency, as symbolized by the arrow ‘A’.
- 0° phase shift f_0 of the CRLH unit cell: The operation frequency could be dynamically controlled by varying f_0, as shown by the arrow ‘B’

Possibly the longest e-mail traffic in our lives to complete this work

13.08.2008; Kagan Topalli wrote:

Dear Julien,

Sorry for my late reply. I was on vacation when I have received your message. I have been in the office since Monday and I have now time to reply your e-mail.
Everything is fine for my side. I am still in METU but in the recent months, there has been some exciting events for me. I was quite close to move to San Diego to work with Rebeiz. Rebeiz sent an e-mail to Prof. Akin in April whether he has a post-doc student that can come to US (Prof. Akin and Rebeiz knows each other from University of Michigan). Prof. Akin offered me to him. He responded immediately stating that he knows me from my work since he reviewed one of my paper (he has reviewed the phased array paper in last August. He has even declared his name and said "Congratulations for the good work"). That was great for me! In his second e-mail, he also stated that "it would be nice to have an interview with Kagan if he comes to MTT in Atlanta". Prof. Akin replied this e-mail after a month and it was too late because he chose another student. He told that he chose him because he is currently in US. Although the result was disappointing, I was glad to hear that my works are appreciated by a high-level man working in the RF MEMS field.
At the beginning of July, the professors dealing with RF MEMS offered me to postpone my post-doc plans for a two years. Because a big project (with a funding of more than 10 million dollars) will start in a few months and it will be difficult for them to handle the RF MEMS part of the project if I leave. They offered me somehow a technical leadership (I will guide a number of master and Ph. D students) and offered me a better salary :). I felt that it will be a wise thing if I leave here for post-doc because the plans regarding RF MEMS would probably change when we are in post doc because the research would be possibly stuck (there are not so many experienced students in the RF MEMS group). It would be quite difficult to find a position dealing with RF MEMS when I come back to METU after post doc. I asked many people before giving my decision and at the end I decided to stay here two more years. I think it will be nice to have such an experience in such a big project. We will see what will happen.
Mehmet is finishing his Ph. D in a few months and he has a military service. I do not have any military obligation since I have a health problem (maybe I have told you that I have hemophilia which is an illness related with bleeding). So Mehmet will not be here for a year which increases my workload. He will also come back to be in the project after completing his military service. He will also have an important position in the project.

This is the summary of the news for the job.

The kid is growing very fast and he is becoming more stronger. He is now a challenging competitor in the wrestling activities with his inexhaustible energy. You can see a photo of us in the attachment.

Regarding your measurements, I was glad to hear that "at least" some of the devices are operational. I have some responses to your summary:

(i) I was also quite suspicious about the beams without any small arms because they have very low spring constants. They were suffering from the residual stress in the structural layer forming the beams as I have observed under surface profiler. I believe that we have to concentrate on the ones with the "small arms".

(ii) I think the stiction problem after release are generally observed for the ones without small arms, right? If so, this is again due to the same problem explained in (i).

(iii) This is strange. I will check the layout and find a reasoning for that. Do you observe the breakdown for both of the sets of devices? By the way, is there an ID number on the petri dish carrying the samples? If so, please send it to me and I will check the process history of them.

The graph that you have sent me was so clear and nice. Thank you. Here in METU, the hysteresis behavior is also observed with simple RF MEMS switches that we have fabricated. You can check it also by measuring some structures (shunt bridges on CPW) on the sample that you have. You will see many DMTL structures at the left side of the wafer and many unit cells of DMTLs close to them. By the way, what I mean from hysteresis is that the actuation and release voltages are different in an RF MEMS beam. This is not due to charging. This is a normal mechanical phenomena as you probably know. The bridges require less voltages to stay in the downstate if they are not so stiff. Charging problem changes the values of the actuation and release voltages. I think my explanation will be clear with the details that is give below:

My comment regarding the graph is:

Everything is clear **up to 9 V**. The electrostatic force (Fe) is increasing, the mechanical restoring force (Fr) is opposing. Fr is larger than Fe. The beam is in upstate but the height is reducing to provide the equilibrium between Fe and Fr.
At 10 V, the first collapse occurs. It is an intimate contact of the beam, where a portion (the edges) of the beam is touching to the membrane. Please note that the beam has a buckled shape looking like a cap of a sphere in the upstate before applying any voltage. Even the ones with small arms look like a hemisphere, where the center of the beam is higher than the edges, as I have observed with surface profiler measurements. I will send you a measurements asap to further clarify the issue. I hope it is currently clear in your mind.
Between 9 V and 10 V, the beam is not stable. Fe exceeds Fr as you increase the voltage from 9 V. The edges of the beam (which is closer to the dielectric) is touching to the dielectric in instances, but the dielectric is suddenly charged which decreases the electrostatic force. The mechanical restoring force of the beam and charging are opposing to the voltage you apply. The beam moves up and down in the close proximity of the dielectric.
At 13 V, the second collapses occur. It is the full contact of the beam. The center of the beam (the highest part of the beam) is touching to the dielectric. The highest loading capacitance is obtained.
Between 10 V and 13 V, the center part of the beam is vibrating on top of the dielectric. It touches and bounces back due to the same reason I have explained above. What I mean is, the edges of the beam remains on the dielectric, the center part of the hemisphere-looking beam is touching to the dielectric in instances, but the dielectric traps charges which decreases the electrostatic force.
As you decrease the voltage **from 13 V to 8 V**, the center part of the beam starts to go up. The center part is not vibrating because there is no reason to move the beam downwards. Electrostatic forces starts decreasing. The restoring forces at the center of the beam is strong so it moves upwards directly as you decrease the voltage from 13 V. The edges of the beam remains in the downstate, because the restoring force of that portion is not so strong.
As you decrease the voltage **from 8 V to 5 V**, the edges of the beam starts moving up (similar to the previous item). The release voltage is 5 V. It is smaller than the collapsing voltage (10 V) of this portion of the beam. This is normal, and observed in many RF MEMS switches with small spring constants (restoring forces). These type of switches are actuated at higher voltages but comes back to upstate at a lower voltage.
Between 5 V and 0 V, the beam is in the upstate and height of the beam increases as you decrease the voltage. It is an analog region as you have indicated.

If you repeat the experiment several times (maybe many many times, I do not know) you would probably see an increase in the actuation voltages. For example, first collapse starts occurring at 11 V (instead of 10 V) and the second collapse occurs at 14 V (instead of 13). The release voltages also change. For example 5 V release voltage would shift 6 V. This is called screening which is a consequence of charges trapped in the dielectric.

If you repeat the experiment several times, the beam may stuck but it seems that the restoring capability of the center part of the beam is quite strong that it start moving up as you slightly decrease voltage. However, I am not so sure about the edges of the beam. These parts can remain in the downstate (sticktion) since it seems that the restoring force of this region is not so high (there is a large difference between actuation voltage and release voltage which are 10 V and 5 V).

(A) Could you provide me an information regarding the waveform you apply for biasing? For example, we are using bipolar actuation (very fast square wave changing between +20 and -20 V, which is generated by a custom circuit consisting of high power transistors.) The rise and fall times are so small that the switch cannot respond that change if we want to keep the switch in the downstate. When we apply simple DC voltage we observe a stability problem if we want to keep the switch in the downstate.
(B) Is it the result of a sample with the beams having "small arms"? I think you could not obtain any meaningful data from the others, right?

I have tried to assist you as much as possible. If you need more samples, please inform me. I believe that you can publish a paper on these devices with these interesting RF measurements. If you believe that we can publish a paper (I think the devices with small arms can be reported only), I can convince the professor to work on a number of new wafers for you, if you need. As you understand, I am willing to collaborate with you but I have different assignments given my boss :). For the mask set including your devices, I have some wafers that are already processed up to a level and the process can be finished in a shorter duration compared to previous run. Please also note that I have another sample that are ready for the measurements. The mechanical behavior of the beams may require further analysis and can be considered as a separate work.

We have discussed in one of the previous e-mail that I can provide you some data for you such as surface profiler (without actuation) and SEM images. If you remember we have also discussed about applying an actuation voltage under surface profiler. I have told here to my colleagues here. It seems that it will not be so easy due to various difficulties. These experiments are performed using Dynamic MEMS analyzers attached to probe stations. We will purchase a dynamic MEMS analyzer and a probe station in a year. I think I will be able to provide many nice datas for you when we have that equipment and then we can consider a work on mechanical behavior of the beams. However I believe that your measurements results can be presented even if we do not have any profiler images whilke actuating the beams. The hysteresis behavior (which allows you to obtain many states) provides a nice information for a reader.

I hope my comments are clear enough. I know it is a quite long e-mail, and I hope it will not bother you. I look forward hearing from you soon.

See you!
Hoscakal,

13.08.2008; Julien wrote:

Hello Kagan !

Well that is the longer reply I ever saw, thanks for the time spent to explain it all (private and job) ! On my side I am going to Lausanne for 5 days this afternoon, so I am 'quickely' writing this e-mail so that I can sent it before I leave ..

First, nice to hear about the consideration form Rebeiz ! However it seems bad if you did not get the job because of Prof Akin delay in replying .. However you seem happy with the program to come in METU. Is that project a public or private funding ? By curiosity could you tell me more about the topic ?
... and thanks for the photo, you both look very good ;) !

Now concerning our MEMS... I will try to answer your question and remarks as clearly as possible.

First, note that the measurements I sent are indeed for a device with the 'arms ' !

" (ii) I think the stiction problem after release are generally observed for the ones without small arms, right? If so, this is again due to the same problem explained in (i). "

Yes, but I have to admit I am now not sure if some with arms were not also stuck. It is stupid from my side, I should have written down better all my observations about failure and mechanics during measurements. The thing is that I was more focused ont the EM response of the functionning devices that on 'mecanical' issues, which I now regret not to have done better.

" (iii) This is strange. I will check the layout and find a reasoning for that. Do you observe the breakdown for both of the sets of devices? By the way, is there an ID number on the petri dish carrying the samples? If so, please send it to me and I will check the process history of them. "

I think that happened with both sets. I must check that to be sure (I dont need to redo measurement to see that!), when I am at the office but now I am at home. I will let me a note and check !

Now, about the hysteresis and all that. Thanks for you clarification that hysteresis is not necessariliy due to dielectric charging. I now remember that i knew about that, but had forgotten it since then, so that was most useful !
Your detailed explanation of the different 'phases' in the actuation is very interesting. I also had the same kind of explanation (as you could see from what I wrote on the graph), but without all this detailed interpretation you give. I guess you can deduce that from the shape of the membrane observed for the profilometer before actuation (the semi-sphericla shape) in conjunction with the graph I provided ? I mean, you did not made actuation test on your side right ?

One clarification to make sure we understand each other. You explained that hysteresis in general can exist even without dielectric charging, which I understood and agree. I guess you would agree that in this case of NO dieclectric charging, the achievable stable states of the MEMS are the same when increasing and decreasing the voltage; only that each state correspond to a different voltage in increasing and deacreasing voltage curves.

However, if I understand well your explanations (see Between 10V and 13V and Between 13 V and 8 V), then you agree that it is indeed dielectric charging that makes that when decreasing the voltage, we can reach some states that were not stable when we were increasing the voltage ! Do you agree ?

In other words, WITH dielectric charging, not only the voltage is different when decreasing (as is the case even without diel charging), but they are also new stable state on the 'return' curve ! As I mentionned in my former e-amil, this is practical useful since it gives us more stable states !!! So it might be interesting to study it...well see the the end of my mail about that.

Next, you mention you are not sure that the restoring capability of the device. What I can tell is that I did several cycle with the device from which I sent the measurement and that it was still ok. However with some other devices it was not the case. I am simply applying DC voltage 'by hand' without waveform, which is how I could observe the different actuation phases. I dod not really understand whatr you meant with "When we apply simple DC voltage we observe a stability problem if we want to keep the switch in the downstate. ". nAgain, ote that the measurements I sent are indeed for a device with the 'arms ' and that I did not get smth nice without the arms.

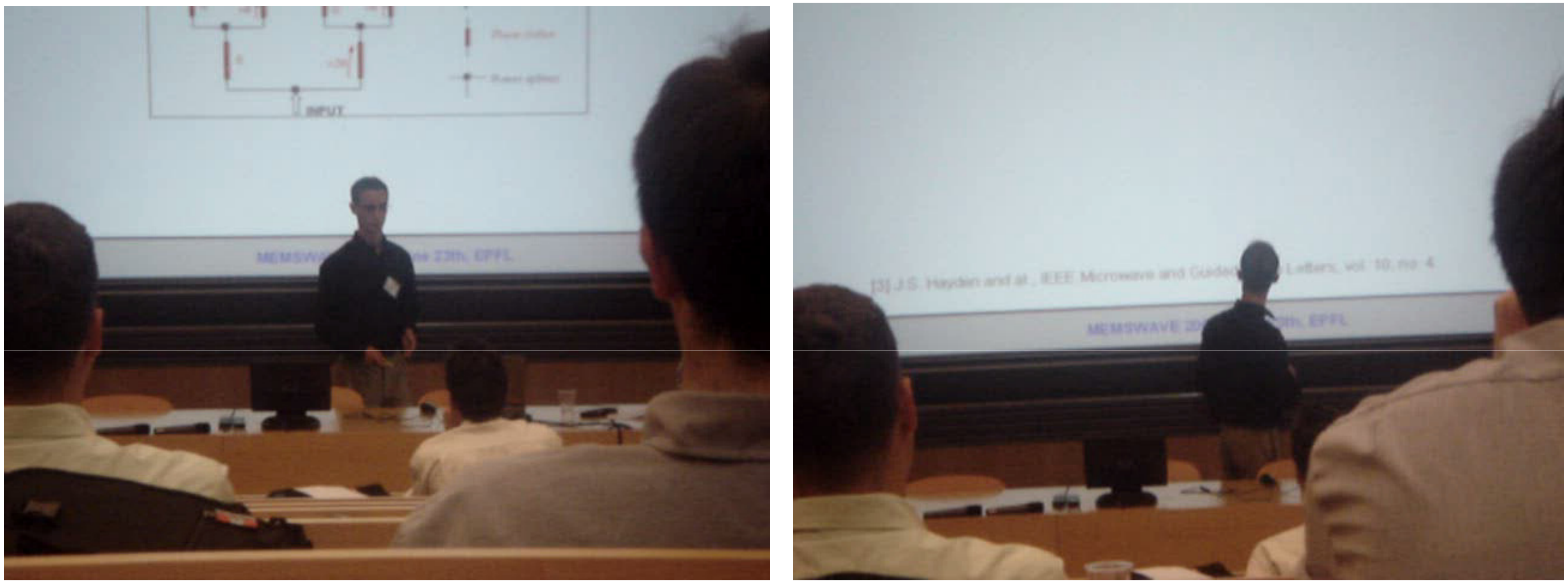
Now, I want to tell you about what I am thinking about possible further step as well as publishing, considerning what you wrote to me. First, note that that the initial emphasis of the work is the EM design (these are so called CRLH-TL-like phase shifter, you might know about it, but anyway we can discuss it more soon) rather than the MEMS mechanical properties. However, it just appear that there are alos nice things to observe there; however, if we want to present some thing about that, then as you suggest we need to make some more tests such as testing more devices (possibly on the new wafers) to check the repeatability of the phenomenon. Concerning measurement of actuation under profilometer maybe you can do it without probe station, if you just manage to fit a DC probe (this is just a kind of needle you attach to a simpler probe holder). Indeed, the device for that just have to big pads to apply DC needles rather than pads for RF probes. Then you only need a DC source more. However I understand this is problematic so we can just forget the idea if that is not feasible.

Now let me link that with what I envison to publish. I have been thinking (and more or less already started) to make a Electronic Letter. This is very short and I could present the device and EM results without entering into details about the mecanical stuff. Of course smth would have to be said about the hyteresis, but that can be very brief (2-3 sentences) and I can stay that this is still under investigation (you can do that in a Letter !). Then I would just put 2-3 sentence with smth like ' dielectric charging allows an extended range of stable states.. indeed, when decreasing the voltage.. this has to be more studied int erms of repeatability etc.". In this paper I would like to put you as second author. However I have to admit that it feel a bit strange putting more people of METU than you, for obvious reason I guess. However, I want you to tell me if it is fair and ok to do so; i mean, should I also put Mehmet ? It is just that I dont know what work was done by each of you; anyway the important thing is that I dont want to offend anyone and be fair. Anyway before deciding on that let us look at my next point...

Now, seeing all your nice explanations about the actuation and that device were again being fabricated, I thought this could also be explained somewhere. Then I thought: we can also do a conference paper, with the same results as in the letter (I allow some overlap between a conference and a journal paper), but extended with some nice electroMechanical characterization ! This could be perfect for EuCap ? The deadline for abstract is in about a month, but the final paper is in January. Do you think we could have devices and that you could make some mechanical test by January (I could also do some of course) ? Then in this case if there is not only the RF things in the paper, it would be logical to put you and Mehmet (and others?) as authors. Then it matter less if someone is present in the Electronic letter or not I guess if we decide we also make this one !?

Well I guess I have written everything... man this is also the longest e-mail I ever wrote !!!!!
Looking forward to your answers !
Que te vaya bien (in espanol ;) !)
Julien

June 2005: Julien was presenting a paper at MEMSWAVE conference




Berlin