frequency of the typical DSPN chip pulse. The chip pulse energy is assumed normalised to the value \( T \), the typical chip duration, so that the mean received signal power over a statistically long fading experience turns out to be unity.

For mathematical tractability and illustrative potential, the chip pulse spectrum now chosen for substitution into eqn. 1 is the familiar pure real rectangular baseband form

\[
U(t) = \begin{cases} 
T \sqrt{(2\pi)} & \text{for } |t| \leq \pi/T \\
0 & \text{otherwise}
\end{cases}
\]

where the chip has been normalised to energy \( T \), as mentioned above.

**Analysis:** Substitution of eqn. 2 into eqn. 1 leads directly to

\[
\sigma_s^2(\sigma) = T \int_0^\infty \left[ 2 \tan^{-1} \frac{t}{T} - \ln \left( 1 + \frac{t^2}{T^2} \right) \right] \mathrm{d}t
\]

where \( T \) is normalised time, equal to \( T/2\Delta \).

It is now instructive to plot the variance of received signal power, \( \sigma_s^2(\sigma) \), against chip time \( T \) in units of \( A \) (Fig. 1).

Clearly, for small \( T \), the variance exhibits a linear dependence on \( T \). Straightforward limiting procedures lead to the asymptotic relation

\[
limit_{T \to 0} \sigma_s^2(\sigma) = x T = T/2\Delta
\]

and for large \( T \) the variance is just unity, which corresponds to Rayleigh fading under the present normalisation to unit average received signal power.

**Discussion:** Clearly the desired mitigation of fading has taken place, as the variance of received signal power with antenna motion becomes linearly proportional to chip time, and therefore inversely proportional to DSPN signal bandwidth. Now the right side of eqn. 4 becomes a more direct expression of that bandwidth dependency if the chip bandwidth is redefined in hertz frequency as **mitigation bandwidth**

\[
W_s = 2T
\]

which is just four times the Hertz baseband chip bandwidth. In terms of mitigation bandwidth eqn. 4 becomes

\[
limit_{T \to 0} \sigma_s^2(\sigma) = 1/(W_s \Delta)
\]

Now eqn. 6 may be accepted as a canonical definition of the mitigation bandwidth of any DSPN signal operating within the infinite dense scatter environment, as long as the signal variance becomes inversely proportional to bandwidth as bandwidth becomes large. Other investigators may seek to verify the generality of that inverse relationship and to calculate mitigation bandwidth for various chip pulse shapes and spectra. For general reference, many traditional definitions of bandwidth are given in Reference 7.

© IEE 1993

17th February 1993

F. Amoroso (271-D West Alton Street, Santa Ana, CA 92707-4171, USA)

References

**SELF-ASSEMBLY OF THREE-DIMENSIONAL MICROSTRUCTURES USING ROTATION BY SURFACE TENSION FORCES**

R. R. A. Symms and E. M. Yeatman

**Indexing terms:** Microstructures, Nanotechnology

The authors propose that automatic, parallel and self-limiting operations can be performed to reconfigure microstructures into full three-dimensional geometries, using the surface tension forces provided by molten solder to perform out-of-plane rotation of flexible hinges. Analysis is presented which indicates that the final angle of rotation can be controlled through initial solder volume, and that the forces are easily sufficient for the particular example of silicon micro-mechanical devices. However, the principle is general and could be applied to other materials.

**Introduction:** Great strides have recently been made in the invention of new processes for fabricating small mechanical devices. Two advances are notable: the sacrificial layer process, developed mainly in the USA [1], and the German LIGA process [2]. The former is a modified CMOS process, based on the repetitive use of optical lithography for surface patterning and the removal of sacrificial material to provide clearances. This allows the construction of complex mechanisms in polysilicon, albeit of shallow depth (<50 μm). In the latter process synchrotron X-rays are used to project a surface pattern into the bulk of a thick resist layer. The resulting relief structure is replicated by electroplating and embossing. Repetitive use of this method is less advanced, but much deeper structures (~500 μm) can be made.

Both methods provide only quasi-three-dimensionality, in that the structures formed are all based on projections of 2-D surface patterns. To alleviate this restriction, one could reconfigure structures previously fabricated by surface processing. One approach would be to follow the fabrication of a quasi-2-D structure with a repositioning step, involving the motion of
only a single degree of freedom for example, controlled rotation out-of-plane. Manual rotation of individual features is certainly possible and has already been demonstrated using polyimide hinges and wing-like structures fabricated by sacrificial layer processing [3]. However, automatic rotation of many structures in parallel has yet to be achieved. There are two problems; supply of the torque and control of the final angle. We propose that both may be solved by the use of surface tension forces, using an extension of conventional solder-bump technology.

Analysis: We shall illustrate the basic principle of out-of-plane rotation by surface tension forces using the simple two-dimensional geometry of Fig. 1a. Here a movable flap of breadth b and thickness t is attached by a flexible hinge of length 2w to a fixed baseplate. In a silicon-based process, the flap might be formed from polyimide using sacrificial layer processing, whereas the baseplate might be a silicon substrate. The hinge might be a ductile metal such as AuSi, or a polymer. A solder pad is deposited on the flexible hinge to a height h. This solder wets the hinge material but not the surround, so that the hinge acts as a land. In practice, this might require the use of an additional surrounding coating.

![Fig. 1](https://example.com/fig1.png)

**Fig. 1** Stages in the rotation of a hinge

a) Before melting of solder pad
b) During rotation
c) After full rotation and solidification of solder

If the structure is heated to the solder melting point, the solder will deform so as to reduce its surface energy. The energy given up can carry out the work needed to deform the flexible hinge and to raise the centre of gravity of the flap. The geometry will stabilise when a torque balance is achieved. At this point, the temperature may be lowered to freeze the solder (Fig. 1c). The torque on the hinge is caused by two forces; an excess pressure \( P_w \) inside the liquid solder due to its curved boundary and the surface tension force \( F_s = \gamma \). The first is found from the Laplace equation, which reduces to \( P_w = \gamma / r \) in two dimensions (r being the radius of curvature). This generates a clockwise torque \( T_w = \gamma w^2 / 2r \) per unit length of hinge. \( F_s \) acts on the end of the hinge at the contact angle \( \alpha \), and generates a counterclockwise torque \( T_s = \gamma w \cos \alpha \) per unit length.

The geometric factors \( \phi, \theta, r \), as shown in Fig. 1b, can be related by assuming the liquid is incompressible. Then the initial and final cross-sectional areas can be equated, giving

\[
2wh = \left[ \omega^2 \sin (\theta) + r^2 \sin (\phi/2) \right] / 2
\]

Using the fact that \( r \sin (\phi/2) = w \cos (\theta/2) \), and defining the normalised initial height \( \eta \) of the solder pad as \( \eta = h / w \), we then obtain a single equation linking \( \phi \) and \( \theta \)

\[
\cos^2 (\theta/2) (\phi - \sin (\phi/2)) = \sin^2 (\phi/2) / 4 \eta - \sin (\theta)
\]

(2)

With some manipulation of the geometrical factors, the net counterclockwise torque can be shown to be

\[
T = \gamma w \sin (\left[ \theta + \phi / 2 \right]) - \sin (\phi / 2) / 2 \cos (\theta / 2)
\]

(3)

The torque can also be found by considering the change in surface energy, \( \gamma s \), with angle of rotation, giving \( T = -\gamma d s / d \theta \). This yields the same results, but provides an alternative physical interpretation.

![Fig. 2](https://example.com/fig2.png)

**Fig. 2** Normalised torque \( T / \gamma w \) against angle of rotation \( \theta \), for different values of the normalised solder pad height \( \eta \)

(i) \( \eta = 1.0 \)
(ii) \( \eta = 0.8 \)
(iii) \( \eta = 0.6 \)
(iv) \( \eta = 0.4 \)
(v) \( \eta = 0.2 \)

Fig. 2 shows the variation of torque with rotation angle for various solder volumes. This demonstrates two important points. First, there is a stable angle where the torque is zero, and secondly, the position of this stable point can be controlled over a wide range by varying \( \eta \). In Fig. 3 this relationship is shown explicitly. Final angles can be calculated by setting the net torque in eqn. 3 to zero. For the special case \( \phi = \pi / 2 \), this requires a pad height of \( \eta = \left[ 1 + \pi / 4 \right] / 4 \), or 0.6427. In this case, the stable free boundary is semicircular, as shown in Fig. 1c.

![Fig. 3](https://example.com/fig3.png)

**Fig. 3** Final angle \( \phi_f \) against normalised solder pad height \( \eta \), and normalised starting torque \( T_0 / \gamma w \) against normalised solder pad height \( \eta \)

From eqns. 3, the starting torque (i.e. for \( \theta = 0 \)) is \( T_0 = \gamma w / \sin (\phi/2) \). This is plotted in Fig. 3. The maximum will be \( T_{max} = \gamma w \) per unit length. At this point, the liquid cross-section is semicircular, so that \( \eta = \pi / 4 \). \( T_0 \) is still close to its maximum value when \( \eta = 0.6427 \), i.e. for 90° rotations.

We now consider the relative magnitude of the torque due to the weight of the flap. For \( \theta = 0 \) this is given by \( T_F = \rho b \delta y / 2 \) where \( \rho \) is the density of the flap material. \( T_F \) must be overcome by the starting torque \( T_0 \) if the flap is to rotate. Using the approximation \( T_0 = T_{max} \), and assuming that the hinge width is comparable to the flap thickness (both might be \( \sim 10 \mu m \), we obtain a simple expression for the maximum breadth of flap that can be lifted:

\[
b_{max} = \sqrt{\gamma / \rho g}
\]

(4)

**ELECTRONICS LETTERS** 15th April 1993 Vol. 29 No. 8
For solder, $\gamma$ depends on alloy composition and temperature [4], but for a mix of 95% lead and 5% tin it is approximately 0.4-0.5 N/m over the range 300-450°, i.e. just above its melting point. For a silicon flange ($\rho = 2.33 \times 10^3$ kg/m$^3$), this gives $f_{\text{max}} = 4.4 \times 10^7$, or roughly 5 mm. Note that $f_{\text{max}}$ is the breadth which $T_0$ and $T_T$ are comparable. For breadths ten times smaller (i.e. ~500 mm), the surface tension torque will be approximately 100 times larger than the gravitational torque, which is then effectively negligible. The mechanism should thus be appropriate for typical microstructures.

**Discussion:** Since surface tension forces scale with length, whereas weights scale as length cubed, there must be a point when the torque due to surface forces in any liquid can rotate a component formed from any material. For Si and solder, this is true for structures as large as hundreds of micrometres. The corresponding size scale is likely to include useful applications in other material systems as well.

The rotation of large numbers of components simultaneously could be achieved simply by heating entire substrates. Programming the rotation of each flap through a particular angle might also be performed by using an appropriate initial pad width for each, with a constant solder thickness. Rotated structures should be inherently stable, even if remelted. The basic principle could be extended using flaps attached to other flaps rather than simply to the substrate, allowing more complicated structures (for example, a closed box) to be fabricated. Additional solder pads could be used to improve the relative alignment of rotated features as they approach each other and to form intermediate seams for improved rigidity.

© IEE 1993
11th March 1993
R. A. Sams and E. M. Yeatman (Optical and Semiconductor Devices Section, Department of Electrical and Electronic Engineering, Imperial College of Science, Technology and Medicine, Exhibition Road, London SW7 2BT, U.K.)

**References**


Presently, the distributed feedback (DBR) or distributed Bragg reflector (DBR) lasers are limited to a ~10 nm tuning range when using current injection. However, much broader wavelength tuning has been recently reported for a laser based on a grating-assisted vertical coupler intracavity filter with a single current control [1, 2] and for a sample grating DBR laser with two current controls [3]. For the vertical-coupler filtered (VCF) laser [1], the tuning current was high (90 mA) and hence at the end of the tuning range the laser required pulsed operation. With improvement in device processing and material regrowth and using a filter length that more closely approximates one coupling length, we have now achieved a wide electrical tuning range of 55 nm with a substantially reduced tuning current of 40 mA and under CW operation over the entire tuning range.

A schematic diagram of the VCF laser is shown in Fig. 1. It consists of a gain section (600 μm long) and a monolithically integrated tunable vertical-coupler filter (800 μm long) followed by a window section (200 μm long). The gain section is composed of six compressively-strained InGaAs/InGaAsP quantum wells. The facet of the window section is HR coated. The upper and lower waveguides are formed with $\lambda_c = 1.4 \mu m$ InGaAsP material and $\lambda_c = 1.1 \mu m$, respectively, and the grating period of the filter section is 16 μm. The layer structure in each section and the tuning mechanism are described in detail in Reference 1. The structure is essentially the same as that of Reference 1 except that the filter length has been reduced from 1-3 mm to what we believe more closely approximates one coupling length. The CW light-current characteristic of the laser with no tuning current exhibits a threshold current of 50 mA, with a ~20% external differential quantum efficiency.

**Fig. 1 Schematic diagram of VCF laser**

The measured tuning characteristic at 17°C is plotted in Fig. 2. A tuning range of 55 nm has been obtained by injecting only a 40.5 mA tuning current (for a 48.7 nm tuning toward shorter wavelengths) and applying a ~4.9 V reverse-biased voltage (for a 6.7 nm toward longer wavelengths) into the VCF section. Because of the low tuning current, the entire wavelength tuning was achieved under CW operation without the difficulty of junction heating of the laser. With a reasonable sidemode suppression ratio (SMSR) of >20 dB and as high as 30 dB, the longitudinal modes (cavity modes) were

**Fig. 2 Measured tuning characteristic**

**BROADLY TUNABLE InGaAsP/InP VERTICAL-COUPLER FILTERED LASER WITH LOW TUNING CURRENT**


**Indexing terms:** Semiconductor lasers, Lasers

A tuning range of 48 nm has been achieved with a tuning current of only 40 mA in a 1.55 μm InGaAsP/InP multi-quantum-well laser based on a grating-assisted vertical coupler intracavity filter. Using a combination of current and voltage tuning, a 55 nm tuning range was demonstrated.

Broadly tunable monolithic semiconductor lasers are critical components for many applications, especially wavelength division multiplexed (WDM) networks and switching systems.

664